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RTO LECTURE SERIES 219

Damage Risk from Impulse Noise

(les Risques auditifs et extra auditifs des bruits impulsionnels)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Human Factors and Medicine Panel (HFM) and the Consultant and Exchange Programme of RTO presented on 5-6 June 2000 in Maryland, USA and on 15-16 June 2000 in Meppen, Germany.

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Damage Risk from Impulse Noise

(RTO EN-11)

Executive Summary

High-level noise, especially high-level impulse noise (weapon noise), is potentially hazardous to human subjects (auditory and non-auditory damage). Even in peace time the costs of lost workdays, hospitalization and non-clinical treatment are considerable. Moreover, auditory and non-auditory damage from high-level impulse noise constitute an important limit to combat effectiveness in terms of damage of organs and communication impairment with noise-induced hearing loss. Recent research has shown that the present damage risk criteria have to be adjusted. This has major implications for the protective measures that have to be taken when using weapon systems.

Protection equipment can be very effective when properly used. However, everyday practice shows that the results in the field fall short of what can be achieved. In addition, hearing protection may interfere with communication. New developments in the design of hearing protectors: level dependent, active noise reduction show how the protection and communication requirements can be combined and reached. Recent research on treatment of noise trauma shows that there are possibilities to treat acute trauma when, in spite of hearing conservation measures, noise trauma does occur.

Education, emphasizing the new developments, will improve the effectiveness of hearing conservation and reduce the number of non-auditory accidents. The cost-effectiveness of these educational programs has already been proven.

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Human Factors and Medicine Panel (HFM) and the Consultant and Exchange Programme of RTO presented on 5-6 June 2000 in Aberdeen Proving Ground and on 15-16 June 2000 in Meppen, Germany.

les Risques auditifs et extra auditifs des bruits impulsionnels

(RTO EN-11)

Synthèse

Les bruits intenses, et en particulier les bruits impulsionnels (bruits des armes) sont potentiellement dangereux pour l'être humain (lésions auditives et extra-auditives). Même en temps de paix, les coûts des journées de travail perdues, de l'hospitalisation et des soins non-cliniques sont considérables. En outre, la réduction des facultés auditives et non-auditives, résultant des bruits impulsionnels, limite considérablement l'efficacité au combat en raison des lésions des organes et de la détérioration des communications, qui accompagne les pertes auditives. Des travaux de recherche récents ont démontré qu'il y a lieu d'ajuster les critères actuels d'évaluation des risques lésionnels. Cette conclusion a des conséquences importantes pour les mesures de protection à prendre lors de l'utilisation de systèmes d'armes.

Le matériel de protection peut être très efficace s'il est employé correctement. Cependant, l'expérience montre que les résultats obtenus sur le champ de bataille ne sont pas à la mesure de ce que l'on pourrait espérer. De plus, les protecteurs auditifs peuvent gêner la communication. Les nouveaux développements dans la conception des protecteurs auditifs (adaptation au niveau du bruit, réduction active du bruit..), devraient permettre de satisfaire à la fois aux besoins de protection et de communication. Les derniers travaux de recherche sur les traumatismes occasionnés par le bruit montrent que les traumatismes aigüs peuvent être soignés lorsque, en dépit des mesures de préservation de l'ouie, ce type de traumatisme se produit.

Des campagnes d'information, mettant l'accent sur les nouveaux développements, permettraient d'améliorer l'efficacité des mesures de préservation de l'audition et de réduire le nombre d'atteintes extra-auditives. La rentabilité de ce type de programme de sensibilisation est avérée.

Cette publication a été rédigée pour servir de support de cours pour le Cycle de conférences 219, organisé par la Commission des Facteurs Humains et Médecine (HFM) dans le cadre du programme des consultants et des échanges de la RTO du 5-6 juin 2000, à Aberdeen Proving Ground, Maryland, Etats-Unis et du 15-16 juin 2000 à Meppen, Allemagne.

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List of Authors/Lecturers

Lecture Series Director:

Dr Armand L. DANCER
French-German Research Institute of
Saint Louis (ISL)
5 rue du Général Cassagnou,
BP 34
68301 Saint-Louis
FRANCE

COURSE LECTURERS

Dr Karl BUCK
French German Research Institute of
Saint-Louis
5 rue du Général Cassagnou, BP 34
68301 Saint-Louis
FRANCE

Mr Heinz BRINKMANN
Wehrtechnische Dienstelle für Waffen
und Munition
PO Box 1764
49707 Meppen
GERMANY

Dr Doug OHLIN
US Army Center for Health Promotion and
Preventive Medicine
Aberdeen Proving Ground
Maryland 21010-5403
UNITED STATES

Dr Daniel JOHNSON
Interactive Acoustics Inc
4719 Mile High Dr.
Provo, Utah 84604-6305
UNITED STATES

Mr Richard MCKINLEY
Armstrong Laboratory
AL/CFBA
2610 Seventh St
Wright Patterson, AFB
Ohio 45433-7901
UNITED STATES

TECHNIQUES AND PROCEDURES FOR THE MEASUREMENT OF IMPULSE NOISE

Heinz H. Brinkmann
Wehrtechnische Dienstelle fur Waffen und Munition
PO Box 1764, 49707 Meppen
Germany

INTRODUCTION

Criteria for the measurement of continuous sound have been agreed upon on an international level in the "International Organization for Standardization". These criteria have been promulgated as ISO standards or recommendations.
The different nations, however, disagree on the criteria for the measurement and evaluation of impulse noise. Impulse noise measurement alone cannot be seen as an end in itself, but rather as a tool in the determination of the risk to personnel and materiel resulting from the impulse noise which may be produced by a weapon or an explosion.

HISTORICAL BACKGROUND

As early as in the forties Furrer[1] has presented first impulse noise records in his publication "Die Akustik des Knalles" (The acoustics of impulse noise).

The Ordnance Proof Manual, AIRBLAST PRESSURE MEASUREMENT – ELECTRONIC[2] from 1959 is to my knowledge the first compilation of the US side of some basic terms of modern impulse noise measurement. The importance of impulse noise measurement was considerably increased in 1968 when W. Dixon Ward published the CHABA criterion[3]. This criterion used the measurable characteristics of the blast pressure wave to avoid auditory impairment or to predict possible impairment. Since 1975 the impulse noise criteria important for the USA are defined in MIL-STD-1474. The latest edition from 1997 is MIL-STD-1474D[4].

In Germany impulse noise measurements have been carried out since the beginning of the sixties in close cooperation with medical science. This work resulted in the "Vorläufige Grenzpegeldiagramm zur Hörschädenvermeidung"[5] (Preliminary Limiting Level Diagram for the Avoidance of Auditory Impairment) in the mid-sixties which was repeatedly revised in the following years[6,7] and has been in force in Germany as "Grenzpegeldiagramm zur Hörschädenvermeidung" (Limiting Level Diagram for the Avoidance of Auditory Impairment) since 1974. The German limiting level diagram is also based on the measurable characteristics of the blast pressure wave to predict or even preclude possible auditory impairment.

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[1] FURRER, W.: Die Akustik des Knalles, Schweiz. Arch. angewandte Wissenschaft u. Technik, 12 , 1946
[2] OPM 80-12, ORD-M608-pm, Vol. IV, INSTRUMENTATION 20 April 1959
[3] WARD, W. Dixon: PROPOSED DAMAGE-RISK CRITERION FOR IMPULSE NOISE (GUNFIRE), NAS-NRC Committee on Hearing, Bioacoustics and Biomechanics. WG 57, July 1968
[4] MIL-STD-1474D, Noise Limits, Department of Defense Design Criteria Standard, AMSC A7245, Feb. 1997
[5] PFANDER, F.: Über die Toleranzgrenze bei akustischen Einwirkungen. HNO (Berlin), 13 , 27 (1965)
[6] PFANDER, F. (Hrsg.): Das Knalltrauma, Springer-Verlag Berlin Heidelberg New York 1975
[7] PFANDER, F. (Hrsg.): Das Schalltrauma, Schriftenreihe Präventivmedizin – PM 1 BMVg, Bonn Juni 1994

Paper presented at the RTO HFM Lecture Series on "Damage Risk from Impulse Noise", held in Maryland, USA, 5-6 June 2000 and Meppen, Germany, 15-16 June 2000, and published in RTO EN-11.

In the mid-seventies a Franco-German expert group under the proponency of the Franco-German Research Institute, Saint-Louis, France (ISL) developed a guideline[8] to make possible the comparison of impulse noise measurements performed by different institutions.
The NATO Research Study Group (RSG.6) on the Effects of Impulse Noise has published "Guidelines for the measurement of Impulse Noise from Weapons" in Annex 1 to its final report[9] drawn up in 1987.
Under the proponency of the ISL an expert group has again revised the Franco-German measurement regulation for the measurement of impulse noise in the nineties and promulgated the new edition[10] in 1995.
Since 1993 endeavors are being made to revise the US "Test Operation Procedure TOP 4-2-822" from 1981 and to use this revised version as a basis to elaborate a document valid for the nations of France, Germany, the United Kingdom and the United States. No standardization could be obtained until now also in the case of the current 7th draft of ITOP 4-2-822 "Electronic Measurement of Airblast Overpressure" from 1 September 1999. The special reasons for this will be discussed later.

PROCEDURE

As a mere physical phenomenon impulse noise does not fall under the category of acoustics, but rather under the category of fluid dynamics, gas dynamics and shock waves. In the fronts of the shock waves the pressure, velocity, density and temperature rapidly increase from small values ahead of the shock wave front up to high values in or closely behind the front.
Whenever a round is ejected from the muzzle of a weapon or an explosive charge detonates a large volume of heated gas is released into the surrounding atmosphere. The rapid expansion of the gases into the surrounding medium (undisturbed air) initiates a pressure wave which takes on the form of a shock wave. This shock front initially moves outward from the source point at supersonic speed; however, with increasing distance the velocity decreases to the velocity of sound. Behind the shock front an approximately exponential overpressure drop occurs followed by a lower-amplitude negative phase.
Impulse noise in its ideal form is therefore a double-sided sound pulse of a high acoustic level and extremely short time interval. Its energy is frequently so high as to produce auditory impairment in an unprotected ear. In special cases it may even result in damage to other organs of the human body, such as the lungs, the windpipe, the stomach etc. or in the destruction of non-human structures.

As to the evaluation of possible damage to personnel and materiel the following physically measurable impulse noise parameters may be important:

- peak overpressure,
- rise time,
- time-duration,
- impulse noise spectrum,
- impulse-noise energy.

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[8] VORSCHRIFTEN und RICHTLINIEN zur Registrierung und Auswertung von Waffenknallen, Deutsch-Französische Meßvorschrift für Waffenknallmessungen, BWB-/-DTAT/ETBS-/-ISL, März 1978
[9] FINAL REPORT on the Effects of Impulse Noise, Document AC/243(Panel 8/RSG.6) D/9 Feb. 1987
[10] VORSCHRIFTEN und RICHTLINIEN zur Registrierung und Auswertung von Waffen- und Detonationsknallen, Neufassung der Deutsch-Französiche Meßvorschrift für Waffenknallmessungen, ISL-/-DGA/ETBS-/-WTD91, 10.4.1995

All known international physical evaluation criteria are based on acoustic pressure (here: peak overpressure) and a rise time defined according to the respective guideline.
As to the traumatic effect of the impulse noises (noise in the working environment) the measurement and evaluation of the acoustic alternative pressure must be based on special criteria which will be discussed in the following.

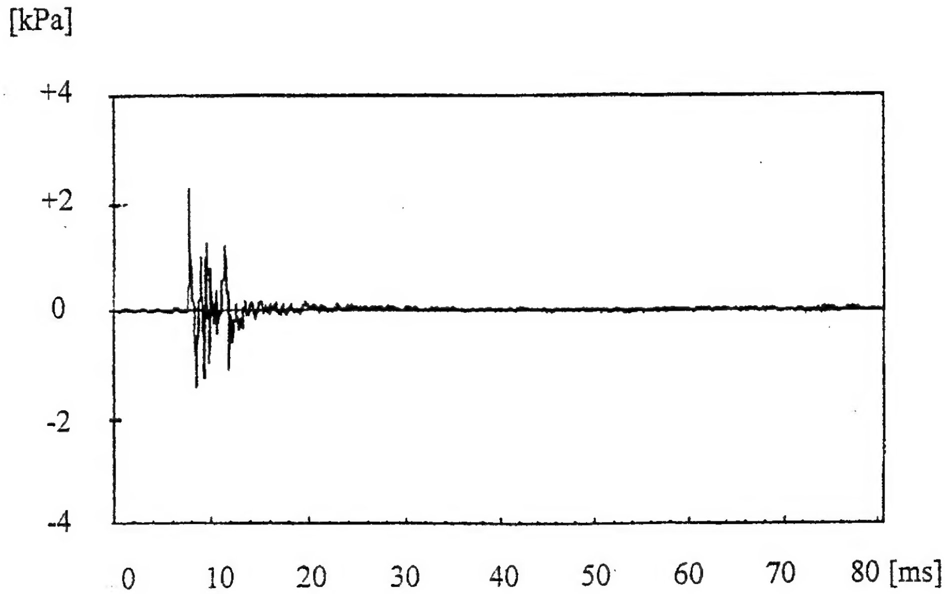

Figure 1: Pressure-time history of the typical impulse noise of a rifle. Acoustic pressure as a function of time.

PEAK OVERPRESSURE

The pressure-time history as shown as an example in Figure 1 is therefore required for the physical evaluation of an impulse noise. As long as the acoustic pressure p is small in relation to the atmospheric pressure p_A there is hardly any distortion (effects in the positive and negative directions are equal = sound in the usual sense). Impulse noises, however, which are studied with regard to possible damaging effects, are often characterized by a positive acoustic pressure portion (p_A + p) which is much greater than the negative portion (p_A - p). The negative portion may reach the maximum value of zero = zero pressure, i.e. vacuum, whereas in the positive phase of the impulse noise high peak pressure levels occur. In the near field of weapons – as determined e.g. during materiel stress tests – peak pressure levels of up to 10^6 Pa = 1 MPa (equivalent to 10 bar) may occur. At the operator or training personnel positions these positive peak pressure values of approx. 200 Pa (= 140 dB) for light weapons and up to 60 kPa (approx. 190 dB) for heavy weapons may vary by more than two decimal powers. The last-mentioned value of 60 kPa or 190 dB is considered as absolute limiting value in the new development of weapons.

RISE TIME

The slope of the pressure rise is of particular importance in the evaluation of an auditory impairment risk especially in the case of impulse sound, because all sound events with shock-like energy supply pass the transmission system of the middle ear fully and without attenuation and are transferred into the liquid-filled cochlea where they exert stress on the sensitive hair cells[11]. The protective reflex of the middle ear muscles cannot respond to this stress due to the relatively long latency of this reflex. It becomes clear that not only the level, but also the level rise time is essential. The determination of the level rise time of impulse noise, however, is difficult and only possible in exceptional cases.
Typically, the pressure rise of the impulse noise is produced by a shock wave which possesses a natural slope so that the front width in the density distribution of the wave, and thus the rise time becomes a function of the peak pressure p. Very weak shock waves with a peak pressure p = 100 Pa (= 134 dB) under standardized air conditions result in a front width of approx. 1.3 mm and a corresponding rise time of approx. 4 µsec[12,13]. According to the present state of the art, such a rise time can just be captured with the most modern pressure transducers.
In the near field of the gunmuzzle, however, a much higher peak value is produced in the course of the pressure history. The front width of the existing moderate up to strong shock waves is reduced to the mean free path of the gas particles (order of magnitude of 10^{-4} mm = 0,1 µm). Thus the slope is much steeper and the rise time very much shorter than 4 µsec. Time-preserving reproduction of the slopes is not possible even with the state-of-the-art reception microphones available at present. It is only possible to state that "the rise time must be very much shorter than 4 µsec".
Although time-preserving reproduction of the slope is not possible, the complete history of the impulse noise including peak pressure and succeeding oscillations is correctly recorded. The time of the positive phase, typically between 0.1 and 5 ms for usual impulse noises is always shorter than the time of the negative phase.
During sound propagation the medium particles move in the direction of propagation in the areas of positive acoustic pressure, in the areas of negative acoustic pressure, however, they move in the opposite direction. Furthermore, the propagation velocity of the pressure maxima is slightly faster, that of the pressure minima slightly slower than the speed of sound. Both effects, the propagation in a flowing medium and the temperature dependency of the speed of sound due to the pressure differences effect a change in the waveform during propagation: the maxima advance, whereas the minima stay behind[14]. As a result, increase-of-slope effects are produced again and again in the shock wave in the near field of weapons, provided that the energy density is high enough. This near field of the weapons, however, is the usual position of the operating personnel.
After a certain path during sound propagation (order of magnitude of 100 m for large-caliber weapons) a stable shock front is formed where increase of slope and the absorption of the higher frequencies rapidly increasing with increasing frequency balance each other.

Only when the sound path becomes longer the absorption of the high frequencies outweighs the increase of slope so that the steep pressure rise levels off more and more. The aforementioned effects, in particular the additional absorption of the high frequencies above

[11] SPRENG, M., LEUPOLD, S. und EMMERT, B.: Mögliche Hörschäden durch Tieffluglärm. Forschungsbericht 10501213-04 im Auftrag des Umweltbundesamtes, April 1988
[12] WECKEN, F., FROBÖSE, M.: Über die Frontsteilheit von Luftstoßwellen bei Ausbreitung über große Entfernungen. Technische Mitteilung T 27/62, Deutsch-Französisches Forschungsinstitut Saint-Louis, 1962
[13] BECKER, R.: Stoßwelle und Detonation. Z. Physik 8, 321-362, 1922
[14] MEYER, NEUMANN: Physikalische und technische Akustik, 4.8 Stoßwellen. Hochschul-Lehrbuch, 1967

grassy soil (in contrast to concrete floor or propagation above water) have been studied recently[15]. The unpleasantly sharp impulse noise near firing weapons therefore sounds increasingly dull with increasing distance from the source of the noise. Moreover, the intensity of the impulse noise, i.e. the peak value rapidly decreases with increasing distance which also contributes to the reduction of the damage risk.

TIME-DURATION

In the Anglo-American states two different time-duration definitions which are required for the application of the CHABA limiting criteria are used[16], the A-duration and the B-duration.

(1) The A-duration: This is the time from the beginning of the impulse noise until the first zero crossing after the drop from peak pressure. This time determines the energy maximum in the impulse noise spectrum, however, it certainly does not capture the time-duration which occurs in complex acoustic pressure histories with reflections after zero crossing. Intensive, short-time post-pulse oscillations (secondary peak values) with lower intensities than the primary peak value may –independent of the spectral composition – cause major impairment of the inner ear[17]. It is therefore important to take these phases into account just like this done in the other time durations.

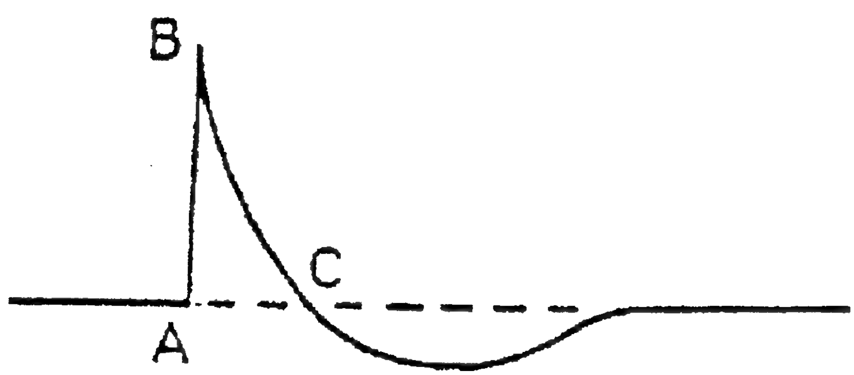

Figure 2: Idealized oscilloscopic waveform of an impulse noise. Peak height: pressure difference $\overline{AB}$; rise time: time difference $\overline{AB}$; A-time according to CHABA: time difference $\overline{AC}$.

[15] FORD, R. D., SAUNDERS, D.J. and KERRY, G.: The acoustic pressure waveform from small unconfined charges of plastic explosive. J. Acoust. Soc. Am., 94 (1), 1993, 408ff

[16] WARD, W. D.: Proposed Damage-Risk Criterion for Impulse Noise (Gunfire), Report of Working Group 57. NAS-NRC, Committee on Hearing, Bioacoustics, and Biomechanics (CHABA), 1968

[17] SPRENG, M.: Auswirkungen des Lärms auf das Hören. Audiol. Akustik, 21, 1982, 66-74 und 94-113

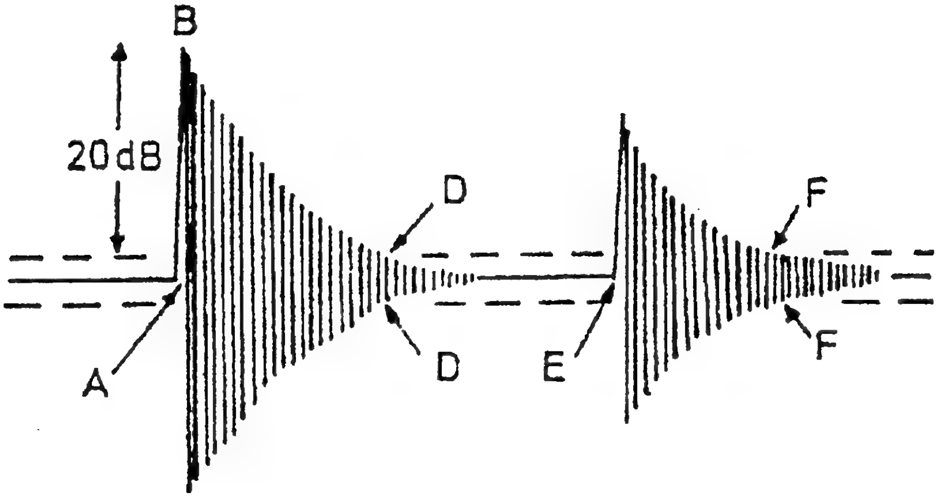

Figure 3: Idealized oscilloscopic waveform of impulse noise. Peak height: pressure difference $\overline{AB}$; rise time: time difference $\overline{AB}$; B-duration according to CHABA: time difference $\overline{AD}$ (and $\overline{EF}$, if reflection is present)

(2) B-duration (pressure envelope duration): The duration of the primary portion of an impulse noise plus the duration of significant subsequent fluctuations. These durations are considered to be the time interval during which the envelope of pressure fluctuations [positive and negative] is within 20 dB of the peak pressure level. The time-duration is then defined as the time from -20 dB before the maximum value of the peak pressure up to -20 dB after the maximum. The use of the definitions of A- and B-duration is practical for the idealized pressure-time histories described. Problems arise, however, with regard to most of the blast pressure records of firing weapons, in particular of impulse noise produced by antitank weapons and mortars and impulse noise within armored vehicles.

The German limiting-level diagram[6,7,19] is based on another time-duration definition.
The time-duration of impulse noise has been defined analogous to a time-duration regulation valid in Germany for aircraft noise as the time duration from -10 dB before the maximum up to -10 dB after the maximum: the **C-duration**[18,19]. The highest pressure peak has thus been selected as reference quantity. This type of time-duration definition is shown in Figure 4.

The value of "-10 dB" is equivalent on a linear scale to a reduction in pressure of approx. $^2/_3$ of the peak pressure value. All subperiods of the impulse-noise history are added on the "-10 dB line" in the positive and negative areas. The time-duration t_w thus is the sum of the periods ($\overline{AB}$ + $\overline{CD}$ + $\overline{EF}$).

[18] BÜRCK, W.: Unveröffentlichtes Gutachten über die Gesamtbeurteilung der Geräuschbelastung für den Menschen auch bei Kurzzeit-Schallvorgängen. Januar 1965
[19] PFANDER, F. (Hrsg.): Das Knalltrauma, Springer-Verlag Berlin Heidelberg New York 1975

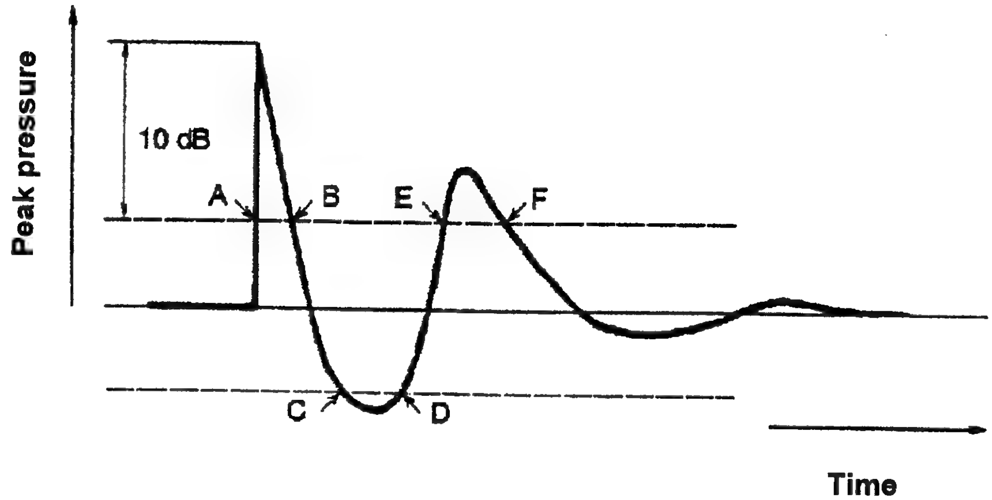

Figure 4: Peak-pressure dependent determination of the time-duration according to the German method; C-duration according to PFANDER

The use of the time-duration definition according to Figure 4 has proven successful in Germany, particularly since the range of interfering influences is often reached when the peak value is reduced by 20 dB[20]. The calculation of the maximum allowable number of rounds depends among other things on the frequency pattern of the individual round: large-caliber guns producing a higher quantity of low frequencies have a longer time-duration because of the more marked post-pulse oscillations. The different effects of low and higher frequencies are indirectly taken into account in the limiting-level diagram according to PFANDER. Low-frequency portions are captured in the calculation of the C-duration by means of the extension of time-duration.
If in order to achieve a common international definition of time-duration another definition is agreed upon, the limiting criteria would also have to be adjusted accordingly.

Another definition of time-duration is used in the Netherlands: the **D-duration** according to SMOORENBURG (see Figure 5). This duration is defined as the time from the beginning of impulse noise until the drop of one envelope around the pressure-time diagram to a value of -10 dB below maximum[21].

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[20] PFANDER, F., BONGARTZ, H., BRINKMANN, H. and KIETZ, H.: Danger of auditory impairment from impulse noise: A comparative study of the CHABA damage-risk criteria and those of the Federal Republic of Germany. J. Acoust. Soc. Am., 67(2), 1980, 628-633

[21] SMOORENBURG, G.F.: Damage risk criteria for impulse noise. in: HAMERNIK, R.; HENDERSON, D. and SALVI, R. (eds.): New perspectives on Noise-Induced Hearing Loss. Raven Press, New York, 1982, 471-490

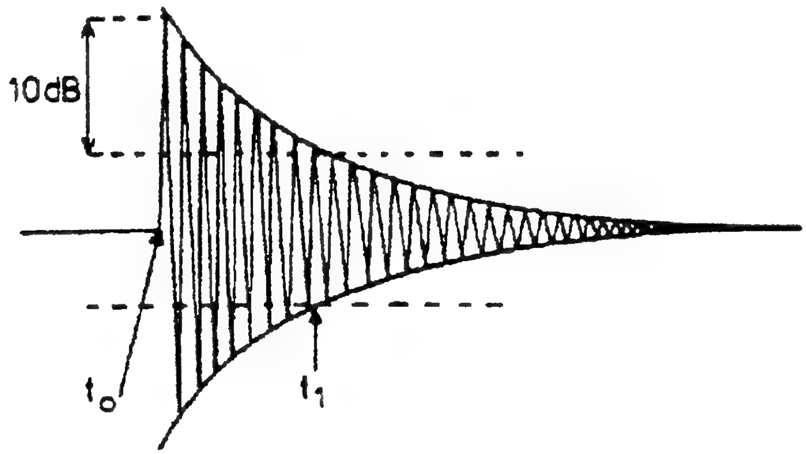

Figure 5: Representation of the D-duration according to SMOORENBURG: time t_0 to t_1

A schematic diagram of the four different time-durations mentioned is shown in Figure 6.

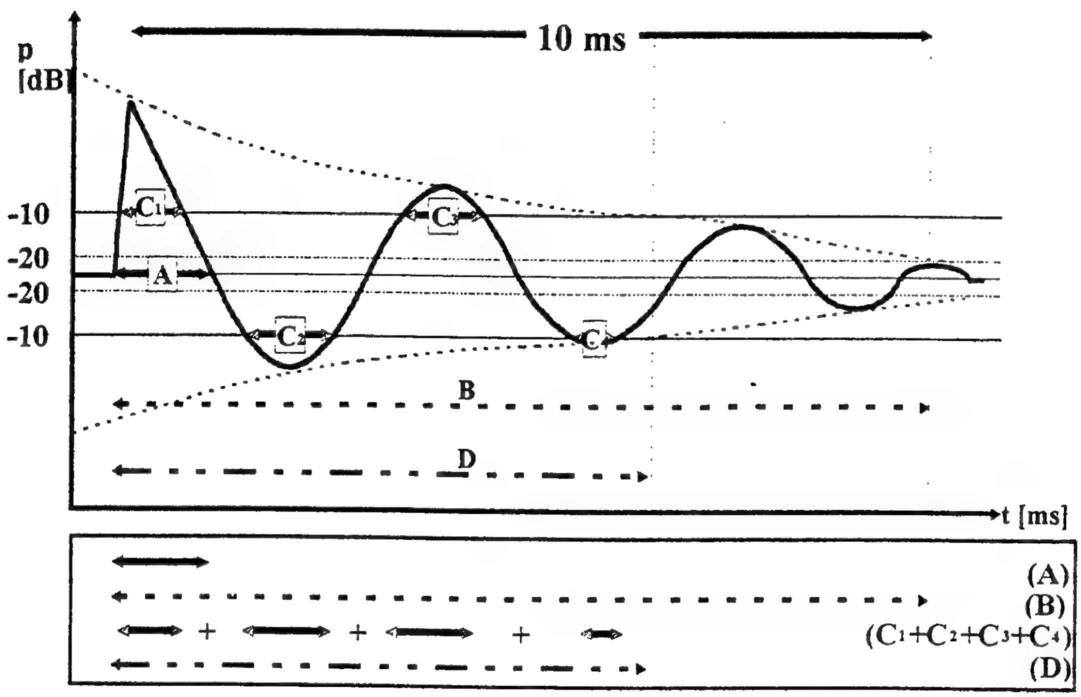

Figure 6: Schematic of different time-durations: A- and B-duration (according to CHABA), C-duration (according to PFANDER), and D-duration (according to SMOORENBURG)

IMPULSE NOISE SPECTRUM

Although not required by the limiting criteria, it seems sensible to examine the impulse noise in its spectral decomposition in addition to its representation in the pressure-time diagram. Already in 1946, FURRER[1] determined the impulse noise spectrum from pressure-time diagrams of impulse noises by time-consuming calculations (Fourier integral equations). In 1958, FURRER[22] presented the spectra of various impulse noises summed up over octaves. This analysis which is shown in Figure 7 proves that due to the bandwidth increasing towards higher frequencies, the smaller spectral portions of the amplitude density spectrum also contained in this range are not to be underestimated.

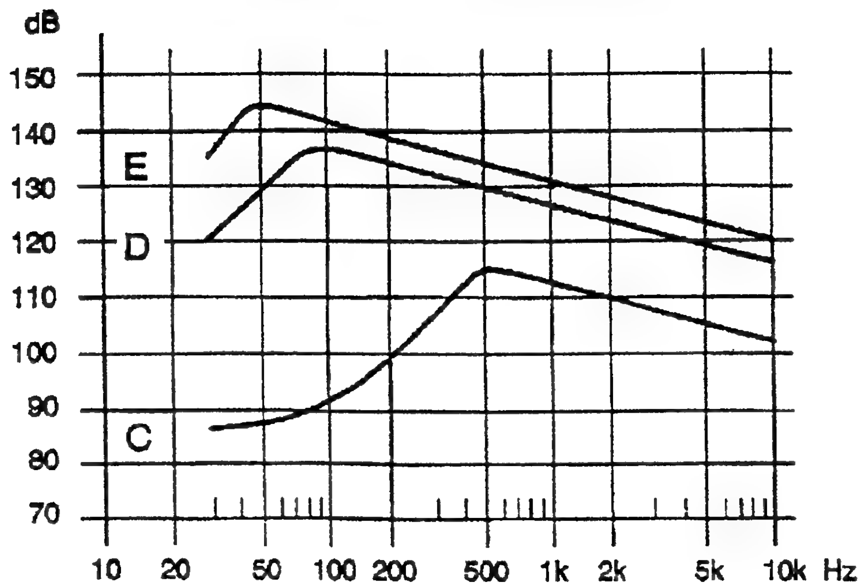

Figure 7: Impulse noise spectra summed up over octaves. C: pistol, 0.85 m distance; D: 7.5 mm gun, 5 m distance; E: explosion of 4 kg TNT, 4 m distance (according to[23]).

Regarding possible damages caused by impulse noise, however, it still cannot be clearly decided whether the spectral decomposition has to be performed with a constant bandwidth or with constant frequency intervals (octave or third-octave spectra).
For this reason it is considered best to perform the analyses with a constant bandwidth = amplitude density spectrum in order to be able to sum up over octaves or third-octaves.
One method to analyze the frequency of impulse noises with digital computers is the Fast Fourier Transformation (FFT) according to COOLEY and TUKEY which provides the desired spectrum from a time signal. With the help of an analog-to-digital converter, the analog pressure-time signal is quantified and stored in the analyzer either directly from the pressure transducer or from the magnetic tape that has recorded the noise. A computer with a suitable program computes the FFT spectrum from the time signal. The FFT spectrum can be represented on a monitor or a plotter within a few seconds after the impulse noise.

In Germany, the impulse noise is recorded by frequency analysis in the form of an amplitude density spectrum and a third-octave spectrum. For this purpose, a work station is used for

[22] FURRER, W.: Lärm und Lärmabwehr. Documenta Geigy, Mensch und Umwelt 3, 1958
[23] FURRER, W.: Lärm und Lärmabwehr. Documenta Geigy, Mensch und Umwelt 3, 1958

which the Franco-German Research Institute, Saint-Louis, France (ISL) has developed the software[24].

An example of this is shown in Figure 8.

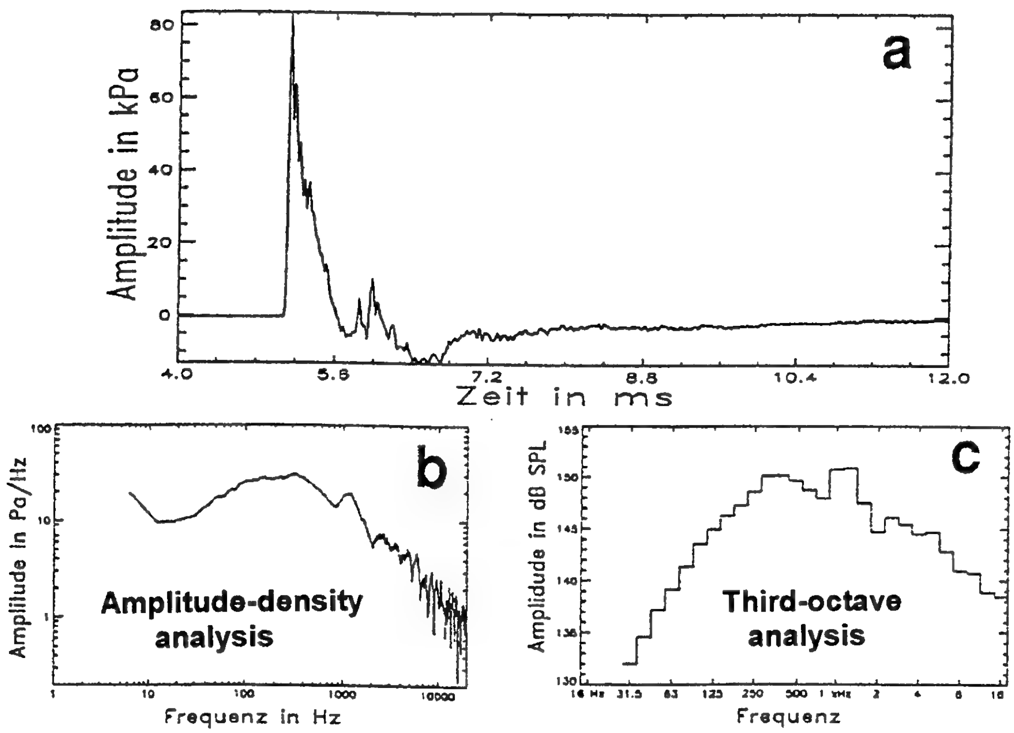

Figure 8: Pressure-time signal (a); with the related amplitude density- (b) and third-octave spectrum (c).

IMPULSE NOISE ENERGY

Lacking a direct measuring method for the impulse noise energy, the readily obtainable parameters of the peak pressure level p_{max} and the time duration t_w were in former times used to determine the previous limiting criteria. The determination of the time duration according to the method common in Germany is physically not necessary and is based only on an

[24] BUCK, K. und BREMGARD, V.: Die digitale Erfassung und Auswertung von Impulslärm, ISL-Bericht 1994

agreement. The use of the limiting level diagram, however, requires the determination of the actual time duration.
The computer-aided evaluation of impulse noise measurements also facilitates an easy determination of the impulse noise energy. The "acoustic impulse noise energy" is the acoustic energy per unit area which is defined as follows:

$$E^* = \frac{1}{Z_0} \int_0^T p(t)^2 \cdot dt \ [J/m^2]$$

where Z_0 is the characteristic acoustic impedance of the air in $N \bullet s/m^3$, p(t) is the instantaneous value of the acoustic pressure in Pa or N/m^2 and dt is the time increment for the scanning of the instantaneous acoustic pressure in seconds. According to BRESS[25] the characteristic acoustic impedance is defined as $Z_0 = 400\ N \bullet s/m^3$. According to the GUIDELINES FOR THE MEASUREMENTS OF IMPULSE NOISE FROM WEAPONS[26], Z_0 is to be $417\ N \bullet s/m^3$.
Up to now, the Bundeswehr Technical Center WTD 91 performed its evaluations following the first definition with $Z_0 = 400\ N \bullet s/m^3$. In fact, $Z_0 = \rho \bullet c$ and is thus dependent on the atmospheric density and the velocity of sound c. Both factors are pressure-dependent in the shock front and thus variable. At a peak pressure level of 160 dB corresponding to 2 kPa, $Z_0 = 409\ N \bullet s/m^3$, while at 180 dB corresponding to 20 kPa Z_0 will already be $492\ N \bullet s/m^3$ [27]. A higher Z_0, however, will have the result that the energy per unit area E* becomes smaller. The energy calculated with the above-mentioned formula is thus slightly higher than the actual energy. Studies performed at the WTD 91 data processing center have shown that at the usual impulse noises of up to approximately 180 dB the deviation is $< 5\ \%$ if Z_0 is used as a constant instead of a variable.
The acoustic impulse noise energy includes the complete acoustic pressure history, while the previously used method with the evaluation of the peak pressure and the time duration leaves out considerable impulse noise portions. For this reason it results in a better correlation with the risk of an acoustic trauma than the method used so far. However, the admissible limiting criteria would have to be adapted for this purpose.

WEAPON IMPULSE NOISE MEASURING PROBLEMS CAUSED BY THE MEASURING METHOD

When measuring the impulse noise in the near field of firing weapons, the pressure transducers can be positioned or mounted in such a way that their membranes are positioned either vertically (direct incidence), parallel (grazing incidence) or backwards (180° offset from the direct incidence) towards the incoming acoustic beams.

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[25] BRESS, H.-J.: Einheitliche Beurteilung von Knallen und Dauergeräuschen anhand des energetisch gemittelten Impulsschallpegels. Rückführung verschiedener Beurteilungskriterien auf die Schallenergie. in: Kurzzeit-impulslärm. Schriftenreihe der Bundesanstalt für Arbeitsschutz und Unfallforschung (BAU) Nr. 12, Wirtschaftsverlag NW, Bremerhaven, 1976

[26] Guidelines FOR THE MEASUREMENT OF IMPULSE NOISE FROM WEAPONS. in: Final Report on the Effects of Impulse Noise / Research Study Group 6, Document AC/243(PANEL 8/RSG.6) D/9, Feb. 1987

[27] BRINKMANN, H.: Messung und Bewertung von Waffenknallen im Hinblick auf Hörschädenvermeidung. in NIXDORF, K. (Hrsg.): Tagungsband „Anwendungen der Akustik in der Wehrtechnik" 1978

In the case of a direct incidence, the following differentiation is made when measuring an impulse noise or shock wave with pressure transducers:

(1) Static pressure: This is the pressure in the undisturbed shock front.
(2) Dynamic pressure: This pressure results from the kinetic energy of the medium particles hitting a pressure transducer and is mainly depending on the shock wave velocity.
(3) Reflected pressure at the membrane of a pressure transducer: A reflected pressure always results when half the wavelength or the smaller wavelength of a pressure portion within the impulse noise spectrum equals the diameter of the pressure transducer membrane or the diameter of the mounting surrounding the membrane. In this case, a pressure increased by 6 dB (= a pressure duplication) is measured for this frequency range. This means that microphones with different diameters will measure different reflected pressure portions. For example, the reflected pressure (6 dB) is of influence for:

(a) a microphone - ø 16 mm	from approx. 10 kHz,
(b) a pressure transducer - ø 5,5mm	from approx. 30 kHz,
(c) a miniature pressure transducer - ø 0,25 mm	from approx. 670 kHz.

For this reason, the aim is to use pressure transducers with the smallest-possible outer diameter and the smallest-possible membrane surface, however, still in consideration of a suitable sensitivity.
In the case of a grazing incidence, only the static pressure is measured. Since the shock front, with its width being relatively small as compared to the membrane diameter, runs across the membrane surface it excites only a part of the pressure-sensitive element. Therefore, the represented rise time of the shock front on the one hand is too high while on the other hand the actual pressure peak is not reached. This is the case especially if the pressure following very short impulses has dropped very rapidly.
In order to be able to achieve comparable results when measuring impulse noises with respect to the stresses imposed on the auditory system on a national and international level, it is mainly important to standardize the measuring technology and methods. In cooperation with the Franco-German Research Institute, Saint Louis, France (ISL), a harmonization both on the French and the German side was achieved in 1978 which resulted in the publication of a joint regulation for weapon impulse noise measurements[28].
It was commonly agreed that the problem of a correct measurement of shock waves (impulse noises) has not yet been solved completely. And it will remain a problem as long as electromagnetic transducers with a finite extension (pressure transducers/microphones) have to be used for measurement. So, if a correct measurement is impossible it should at least be possible to perform a standardized measurement "at any time and at any location". ***Because weapon impulse noise measurements are in general not reproducible, a successful initial measurement is especially important***[29]. In addition, the measuring values should correlate with the common limiting criteria for impulse noise stresses.
Some aspects of the joint agreement are:

(1) Diameter of the pressure transducer including the probe: ≤ 5,5 mm;
(2) unsupported length of the probe (at a ø of 5,5 mm): 80mm;
(3) electric filtering with a low pass with a cut-off frequency of 22.4 kHz (passing of low frequencies, cut-off of frequencies above 22.4 kHz/Bessel characteristic).

[28] Vorschriften und Richtlinien zur Registrierung und Auswertung von Waffenknallen, Deutsch-Französische Meßvorschrift für Waffenknallmessungen, BWB-/-DTAT/ETBS-/-ISL, März 1978
[29] BUCK, K. und BRENGARD. V.: Rechnergestützte Auswertemethoden für Waffenknalle. ISL, PU 312/96

Originally it was assumed that this measuring system could be used for a non-directional measurement (suppression of the reflected pressure portion of the shock wave with the filter). Tests performed at the ISL, however, have shown that a non-directional measurement is impossible with different peak pressure values. For this reason, both the German and the French side agreed upon an identical orientation of the transducers, i.e. a sound incidence of 90°.
The German-French measuring regulation for weapon impulse noise measurements was revised in 1994 and is now available in the bilingual new version of April 10, 1995. No changes were made with respect to the pressure transducer and filtering characteristics. A major modification was performed regarding the inclusion of the digital measuring processing which allows the calculation of the impulse noise energy and the equivalent noise levels as well as frequency analyses in the form of an FFT or a third-octave, in addition to the evaluation of impulse noises according to German, Anglo-American and Dutch criteria.[30,31].
The measuring regulation prepared within the frame of the Research Study Group ON THE EFFECTS OF IMPULSE NOISE[32], specifies a transducer configuration with a grazing sound incidence and the smallest-possible diameter. A 22.4 kHz filtering, however, is not required.
If, however, a grazing incidence cannot be ensured (as, for example, when measuring the impulse noises inside reflecting rooms or inside a tank), indefinable reflection portions at the pressure transducer membrane can distort the overall appearance of the pressure-time history through the rise of a slow, low-frequency pressure wave superimposing the actual impulse[33], while, with the measuring method according to the German-French regulation, these portions would be filtered out.

A "FR/GE/UK/US Four-Nation Standardization Group is working at the standardization of the test procedures mainly for large-caliber guns and ammunition. In the meantime, this group has presented the 7th draft of an ITOP 4-2-822, "Electronic Measurement of Airblast Overpressure"[34]. At present, there are considerable differences with respect to the pressure transducers to be used, including their mounting and the low-pass filtering. An agreement between the German-French point of view and the Anglo-American point of view has not yet been achieved.

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[30] Vorschriften und Richtlinien zur Registrierung und Auswertung von Waffen- und Detonationsknallen, 1995
[31] BUCK, K. und BREMGARD, V.: Die digitale Erfassung und Auswertung von Impulslärm, ISL-Bericht 1994
[32] Guidelines FOR THE MEASUREMENT OF IMPULSE NOISE FROM WEAPONS in: Final Report on the Effects of Impulse Noise / Research Study Group 6, Document AC/243(PANEL 8/RSG.6) D/9, Feb. 1987
[33] HAMERNIK, R.P. and HSUEH, K.D.: Impulse noise: Some definitions, physical acoustics and other considerations. J. Acoust. Soc. Am., 90(1), 1991, 189-196
[34] FR/GE/UK/US International Test Operations Procedure (ITOP) 4-2-822: Electronic Measurement of Airblast Overpressure and Impulse Noise. Draft 7. U.S. Army Test and Evaluation Command, ATTN: AMSTE-CT-T,

New Auditory Damage Risk Criteria and Standard for Impulse Noise

Daniel L. Johnson
Brüel Bertrand Johnson Acoustics
4719 Mile High Drive
Provo, Utah 84604 USA

Abstract This paper discusses the Auditory Risk Criteria as currently being proposed in a draft ANSI Standard. The criteria include two general prediction methods for estimating the hazard. One method, called the survey method, uses the A-weighted energy under a hearing protector to estimate the amount of hearing loss likely to be found for an exposed population. The second method, called a computer modeling method, provides an assessment for each individual waveform of an exposed population. The standard will provide the necessary software for this model. The standard will not provide specific criteria while wearing hearing protection, but instead will provide suggested validation procedures to insure that a specific program in which hearing protection is used actually is preventing hearing loss, either temporary or permanent. Criteria for identifying acoustic trauma and excessive fetal impulse noise will also be included.

A. What is wrong with our current standards and damage risk criteria?

There are several problems with most of the current procedures for the evaluation of impulsive noise. Perhaps the most significant problem is the assumption that the average wearer will properly use hearing protection. Experience has clearly shown that this is a very poor assumption for non-expanding plugs, a poor assumption for expanding plugs, and a fair assumption for muffs Over the last 15 years, it has finally been realized that for non-impulse noise, the laboratory rating for hearing protector performance was far greater than what could be obtained in the field. For this reason, the U.S. National Institute for Occupational Safety and Health (NIOSH) has recently suggested de-rating hearing protector performance. They suggested that muffs should use 75% of their rated attenuation, formable plugs 50% and all other plugs should use only 30% of their rated performance. (NIOSH, 1998). JAYCOR has recently written a report (Chan, et. al., 1999) that suggest the US MIL Standard could be raised by 9 dB as based on human studies using muffs or expandable plugs. If one were to apply these numbers to the problem of high level impulses, we might indeed give a effective reduction of 38 dB for the muffs, thus raising the mil standard by 9 dB. By the same token, we would give the expandable plug only 26 dB, thus lowering the mil standard by 3 dB. For the non-expandable plug, only 13 dB of attenuation would be given, effectively lowering the mil standard by 16 dB. Are such reductions warranted for impulse noise? I don't know. We did use the EAR expandable plug in the Albuquerque studies on occasion. We never observed an auditory failure with this plug However we (EGG) always checked the performance of that EAR plug before a subject was exposed. (Johnson, 1994) This will not be the case when these plugs are used in the field. Soldiers will not always get the proper attenuation of these plugs. Muffs, on the other hand, are hard not to fit right. The Albuquerque studies have shown that leaks around the seals of the muffs should not be very critical. In fact, the blasts themselves caused the muffs to move, which again emphasizes that training when using the muff type protector is not so critical. In the studies at Albuquerque, there was never an auditory failure while using an intact RACAL muff at the non-auditory limits. Thus, the non-auditory limits certainly must set the upper exposure values for auditory risk when using double protection. With a little more caution, the non-auditory limit probably sets the auditory risk limit when using muffs alone. For other hearing protection devices, there will not be any damage risk curves suggested. Instead, there will be a procedure recommended that will qualify a protection program that uses a specific type of protector for a specific type of exposure. The protection program will include a specific type of hearing protection, the training to be used, the management of the program, and the proof that the program works on a day to day basis.

Another problem with the current standards is that they take into consideration the duration of the impulse. At first glance, this has always seemed to be a reasonable approach. The assumption has been that an impulse with a longer duration must be more of a hazard. Even though different damage risk criteria calculated the duration somewhat differently, e.g. the "B-duration", and the 'D-duration", longer duration exposures were always considered more hazardous. Chan, et al concluded that the longer duration impulses were less hazardous. I'm beginning to think they are right.

So what are my suggestions? As the chair of the ANSI working group S-3 62, "The Effects of Impulse Noise", I have hopes that our working group can produce a standard that could serve as a replacement for the mil standard. A working draft has been prepared, however it is not without its faults. One of the features of the draft standard is the incorporation of the damage risk computer model developed at Aberdeen. (Price and Kalb, 1996). At a minimum, I would like to use the model in order to predict the mechanical performance of different hearing protection devices. Obviously, it could be the entire mil standard. However, there is not a consensus of the working group to support that position. In any case, the Aberdeen model will have

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difficulty with the question of the subject fit or soldier's field fit. The current draft standard will also specify the amount of auditory testing needed, including testing in the field. The standard may also have a section on acoustic trauma. In summary, the standard may be more of a set of standardized procedures than a set of hard numbers.

B. Elements of the new standard

This proposed ANSI Standard will present two general methods for the evaluation of the expected "noise-induced permanent threshold shift" (NIPTS) from impulse noise or a combination of impulsive and non-impulsive noise. The two methods consist of a survey method and an auditory modeling method. The survey method will consist of measuring or estimating the A-weighted sound exposure under hearing protection devices. With a small correction factor that relates the gain provided by the human anatomy, the tables of ANSI S3.44 or ISO R-1999, which relate noise exposure to NIPTS, may be used. For exposures in which the peak level is above 140 dB, the auditory modeling method must be used when the ears are unprotected The survey method may be used if the sound that reaches the ear under a hearing protector exceeds a peak of 140 dB if the provided the sound originates outside the hearing protector. The benefit of the survey method is that it provides an estimate of the hazard of the total noise exposure of a person, including both continuous and impulsive noise.

The auditory modeling method consists of measuring the waveform of the impulse either outside or under the hearing protector to be used. The output of the model is a prediction of Auditory Damage Units (ADUs). . The second method is considered more precise because scientific evidence indicates that the basic mechanisms that produce loss in the ear change as the level rises and follow fundamentally different laws. At lower levels where energy measures are appropriate, losses accumulate relatively slowly, over a period years with daily exposure. On the other hand, at higher levels where the loss mechanisms are fundamentally mechanical, the ear may be extensively and irreversibly damaged in a few milliseconds. This change in the ear's response suggests different methods of analysis. Unfortunately, the transition from one loss mode to the other is a complex function of frequency, level, state of middle ear muscles, specific timing of elements in a waveform and so forth. Because of the possibility of instantaneous loss with no warning signs, any time that pressure can be predicted to rise above 140 dB; hearing protection should be worn.

As a result of the uncertainties associated with high level exposures, the auditory modeling method provides a prediction of hazard for the 95%ile ear (most susceptible). The survey method includes the possibility of calculating hearing loss for any percentile of the population with the algorithms in ISO-1999. For consistency in the application of this standard, however, it is recommended that calculation for the 95%ile ear should be used.

To use the auditory modeling method, you run a computer program that will be provided as part of this standard. This program is based on a mathematical model of the human ear designed to predict hazard from intense sounds. It requires that the full-digitized waveform be on a file accessible by the program, typically on a disc. The standard includes the algorithms necessary for importing waveforms for processing by the standard. In addition to analyzing waveforms measured in the free field, this method analyzes waveforms that have been measured at the ear canal entrance or at the eardrum position. Thus, it is possible to evaluate hearing hazard under hearing protectors. Details of the requirements and procedures will appear in an Appendix.

The use of two methods for rating hazard that are based on different premises is an unavoidable consequence of the complexity of the ear's response at high sound pressure levels as well as the accompanying uncertainties in real exposures. If there is a question as to which of the two methods should be applied, the standard will suggest both methods should be used and the greater hazard value accepted unless counter-indicated by audiometry.

The standard also provides a general procedure for qualifying a specific hearing protector for a specific type of waveform. These procedures attempt to take into account the variability in actual protection due the wearer's training the use of the protector, individual susceptibility to the particular impulses, fitting problems of the protector, variability of the impulses, and any other factors that effect the hazard of the exposure.

The standard will also define when acoustic trauma occurs. Possible courses of action will be suggested in an appendix.

The standard will also recommend that a hearing conservation program be implemented whenever individuals are knowingly exposure to levels above 140dB.

Finally, the standard will also suggest that pregnant persons should not be exposed to peak levels above a c-weighted peak of 155 after the fifth month of pregnancy. This recommendation is to protect the hearing of the fetus. The measurements should be at the abdominal wall.

The standard recommends that the evaluation of the non-auditory risk of injury be made whenever the peak level exceeds 180 dB.

C. Specific Details of the Proposed Standard

1. The survey method using A-weighted Sound Exposure:

a General To estimate hearing impairment and risk of hearing handicap as a result of exposure to noise, the average A-weighted sound exposure, $E_{A,8h}$ and/or the noise exposure level normalized to a nominal 8 h working day, L_{A8hn}, (shall be either 1) measured directly by sound exposure meters or integrating sound level meters, or 2) calculated from sound pressure measurements and exposure time and hearing protection attenuation values. Such measurements may be made with instruments that are either stationary or attached to the noise-exposed person.

The measurement locations and the duration of the measurements shall be chosen so as to represent the exposure to noise experienced during a typical day by the population at risk.

b Instrumentation For direct measurement of equivalent continuous A-weighted sound pressure levels, integrating-averaging sound level meters shall comply with IEC 804, type 2 or better.

c Calibrating and checking. All equipment shall be calibrated, and the configuration for calibrating and checking shall be in accordance with the manufacturer's instructions.

The user shall make a field check at least before and after each series of measurements. An electric check of amplifiers, recorders and indicators shall be made as well as an acoustic check of the sensitivity of the microphone and/or the total system. This is especially important when the microphone is placed into the ear canal.

d Microphone positions When the measurement of sound pressure to determine the A-weighted sound exposure and/or the equivalent continuous A-weighted sound pressure level for the unprotected ear, the measurements should be made with the microphone located at the position(s) normally occupied by the head of the person concerned, the person being absent. For measurements made under muff type hearing protectors, the microphone should be located at the entrance of the external ear canal of the ear receiving the higher value of the A-weighted sound exposure or the equivalent continuous A-weighted sound pressure level. All measurements shall be corrected by the pinna/ear-canal-gain function.

For measurements made under insert type hearing protectors, the microphone should be located such that it measures in the cavity between the insert device and the tympanic membrane of the ear receiving the higher value of the A-weighted sound exposure or the equivalent continuous A-weighted sound pressure level. All measurements shall be corrected by the pinna/ear-canal-gain function.

The exact positions at which the measurements are made shall be reported.

e Measurement: Pertinent details of the measuring instrumentation, measurement procedure and conditions prevailing during the measurements shall be carefully recorded and kept for reference purposes. When reporting the measurement result, an estimation of the overall measurement uncertainty shall be stated taking into account the influence of factors such as: measuring instrumentation, microphone positions, number of measurements, time and spatial variation of the noise source.

f Daily exposure to noise over an extended time period. The daily A-weighted sound exposure or the noise exposure level shall be determined for a sufficient number of days and for the individuals under consideration to allow the determination of the average exposure to noise for the years or decades under consideration. If measured directly, the determination of the daily exposure shall be made by instrumentation that provides an indication of the A-weighted sound exposure or the equivalent continuous A-weighted sound pressure level. Such instrumentation integrates the fluctuations of the noise produced by a time-varying noise source or by movement of the person from place to place. The fluctuations may be spread over a wide range of levels and/or be of irregular time characteristic. The fluctuations may also include noises of impulsive character. If the daily exposure to noise is estimated by some method, such as task-based analysis, then the all of a person's noise exposing activities must be considered. As a practical manner, the daily noise exposure may be calculated from a combination of actual measurements and estimates. The daily noise exposures should be combined to provide the average daily exposure to noise over the total number of days for an individual or a group of individuals. When the noise is not the same from day to day, as certainly may occur for impulse noise from training, the equivalent continuous A-weighted sound pressure level averaged over a longer period (not exceeding 1 year) should be adjusted upward so the daily equivalent continuous A-weighted sound pressure level on the worst day is not more than 10 dB higher.

NOTE - For exposure to noise too irregular for this Standard to be applied without the above adjustment, monitoring audiometry is strongly recommended. Monitoring audiometry, in conjunction with audiometric data base analysis, is good practice anytime.

g Use of Pinna/ear-canal gain: Because all of the formula in section 6 of this standard use a noise exposure calculated at the position of the center of the worker's head if the worker was present, the gain of pinna and ear canal needs to be subtracted from the measured or calculated value measured under the insert type hearing protector. The gain ranges from 6 to 14 decibels (Shotland, 1996 and Shotland, et. al., 1994). However, for the purposes of this standard, the gain of 6 dB will be used. Thus 6 decibels will be subtracted from all exposure levels measured or predicted under insert hearing protection.

This correction will not be recommended for muff type protectors.

h Estimation of noise-induced permanent threshold shift, N

1)) The expected Noise-induced permanent threshold shift can be calculated from the procedures in ISO R 1999 or in ANSI S3.44.

2)) Use of NIPTS Values The NIPTS values can be used to calculate the expected hearing impairment in a Population by using the procedures outlined in either ISO R1999 or ANSI S3.44

2. The auditory modeling method (ADM) using the computer model developed at Aberdeen

a. General

The model is based around a theoretically based mathematical model of the human ear designed to predict auditory hazard for sounds with peak pressures high enough that the damage mechanism within the inner ear is fundamentally mechanical (Kalb and Price, 1987, Price and Kalb, 1996; 1991). The model is not only theoretically based; but is structured so that its elements are conformal with the physical structure of the ear. This approach in a standard is not common; however it brings with it many advantages, among them the ability to generalize from specific experimental tests to new situations with a reasonable expectation that the analysis fits. It also allows the analysis to begin at various locations, such as the free field, ear canal entrance, or eardrum position, which means that any waveform measured at such a location can be analyzed. This is important because it makes it possible to evaluate the effect of hearing protectors without having to make assumptions about their attenuating properties. Single number estimates of effect used in the past (CHABA, 1968; MIL STD-1474X, 198?) obviously represent a great loss of information about a protector's effect. Such compromises are no longer necessary.

The presence of various non-linearity's in the ear's response at very high sound pressure levels has made the use of such a model not only desirable but also necessary. For instance, A-weighting can compensate for non-linearities with respect to frequency and as a result is commonly used in noise ratings. However, at very high sound pressure levels where Method II must be applied, the non-linearities associated with middle ear muscle activity and with a physical limit to stapes displacement cannot be adequately accounted for by essentially linear analyses such as filtering[1]. Hence, the necessity for a modeling approach.

b Measurement Requirements Specific to the Model To use existing methods of hazard analysis, some form of summary analysis of the waveform was needed e.g. a peak pressure, some measure of duration (A-duration, B-duration, C-duration, D-duration) or an A-weighted energy. Then a value could be read from a chart that would indicate the risk. The ADM, however, calculates displacements in the ear as a function of time and acoustic pressure. It therefore requires only a digitized waveform of the sound being analyzed as its input. The ADM includes basic algorithms for preparing waveforms for use with the method. Because the ADM allows predictions which include middle ear muscle effects (if desired), there is also a requirement that the waveform be stored in a manner that allows such calculations to be made. Algorithms that allow this will be included with the standard.

c. Format and Waveform Quality The waveform must be stored in ASCI format. Data may include time points as well as pressures or even multiple pressure histories in a file. The input-processing algorithm with the standard can handle the most common possibilities. The ADM represents an immense increase in use of information in the waveform. As a result, an accurate analysis requires a faithfully reproduced waveform. Good vertical resolution requires the use of at least a 12-bit digitizer (16 bit preferable) and good resolution in time requires a sampling rate of 40-50 kHz. If the waveform includes significant amounts of low frequency energy (even near 1 or 2 Hz, as do airbag waveforms) the recording system should reproduce it faithfully. It may be true that the ear doesn't hear such sounds; but low frequency sounds cause the middle ear to become non-linear and modulate the flow of energy into the cochlea. Put in traditional terms, the dynamic range of the recording should be at least 60 dB and the frequency response of the system should be essentially flat from 1 Hz to 20 kHz. The algorithms in the ADM require that the numbers in the waveform being processed be pressures in Pascals. Algorithms included with the standard allow any values to be adjusted so that the calculation will be accurate.

d. Applications of the ADM There are several application of the ADM that are suggested. These are as follows:

1)) The ADM can be used to predict the likelihood of hearing damage from exposures that occur when hearing protection is not worn. When used in this mode, the level that is equivalent to a daily eight-hour exposure to 85 dBA for a year is 250 Auditory Damage Units (ADUs).

2)) The ADM can be used to evaluate the relative auditory hazards of different weapon systems of the same general type.

3)) The ADM can be used to evaluate, for different hearing protectors used correctly, the relative effectiveness against the impulses of a specific type of weapon system.

Note: Because the ADM cannot predict how a hearing protector is going to be worn in practice, it cannot be used to validate the actual performance of a hearing protector.

3 The validation and documentation of hearing protection performance

a. General Because the actual protection against auditory damage of any hearing protective device depends so much how each individual user correctly wears the hearing protector device, the following validation procedures are recommended as standard practice. Because certain types of hearing protectors are more likely to be properly worn than others, the amount of validation will differ for different types of devices. Over the last 15 years, it has finally been realized that for non-impulse noise, the laboratory rating for hearing protector performance was far greater than what could be obtained in the field. For this reason, NIOSH has recently suggested de-rating hearing protector performance. They suggested that muffs should use 75% of their rated attenuation, formable plugs 50% and all other plugs should use only 30% of their rated performance. (NIOSH, 1997). Yet the use of a muff type plug alone was shown to safely protect the auditory system up to the non-auditory limit for exposures of 6 and 100 impulses. (Johnson, 1997). Thus the extent of the validation procedures needed is a function of the type of hearing protection used. In all cases a hearing conservation program should be in place.

b. Testing for excessive threshold shifts in hearing levels. For the recommended test populations indicated in paragraph c of this section, a hearing protector shall be consider validated for use for a specific type of waveform and peak level if the amount of TTS 1 to 5 minutes after the last exposure is less than that shown in table 3

TTS (1-5 min)

No of Users tested (N)	15. <TTS<25	25<TTS<Trauma	Trauma
20	1	0	0
40	2	1	0
80	4	2	1
>80	<.0	<.025*N	<.00125*N

c. The recommended minimum number of users tested for excessive temporary changes in their auditory thresholds follow:

1) Double protection using a muff and an formable plug:

a)) Starting level: Non-auditory limit for all types of impulses
b)) Initial validation None
c)) Yearly validation None

2) Double protection using a muff and a non- formable plug:

a)) Starting level: Non-auditory limit for all types of impulses
b)) Initial validation First 20 users
c)) Yearly validation None

3) Single protection using a muff:

a)) Starting level: Non-auditory limit for non- reverberant impulses
185 dB peak for reverberant impulses
b)) Initial validation First 40 users,
c)) Yearly validation 20 users

4) Single protection using an expandable plug:

a)) Starting level: Non-auditory limit for non-`reverberant impulses
185 dB peak for reverberant impulses
b)) Initial validation First 40 users
c)) Yearly validation 40 users

5) Single protection using a non-expandable plug:

a)) Starting level: 185 dB peak for non-reverberant impulses
180 dB peak for reverberant impulses
b)) Initial validation First 80 users and 10% of all users
c)) Yearly validation The larger of 80 users or 10% of all users

d. Re-verification The purpose of the verification process is to insure that the hearing protection provides sufficient protection in at least 95 % of the users. If the verification fails, then one or more of the following actions should be undertaken before re-verification:

a)) Change hearing protection
b)) Improve training in use of the protectors
c)) Lower exposure levels
d)) Improve motivation on the use of protection.

4. Definition and Recommended actions for acoustic Trauma

a). Acoustical Trauma is considered to occur when the Temporary shift of hearing
2 minutes after exposure at any frequency is greater than 40 decibels. If the audiometric test is accomplished at a time longer than 2 min., the equation below should be used to determine if the TTS is sufficient to be considered acoustic trauma.

Time post exposure of audiogram at the freq. in question	TTS level at which Acoustic Trauma is assumed
<2min	40 dB
2 min to 928 min	15xlog(928/t) dB
>928 min	15 dB

Use of the above equation is for guidance only and assumes that the hearing thresholds of the victim were known previous to the incident. If the prior thresholds are not known, then the standard will suggest that the determination of acoustic trauma must be made entirely on the recommendation of the medical examiner.

b) Treatment The standard will recommend that treatment of acoustic trauma be undertaken. At the minimum, a rest period away from any noises above 75 decibels should be considered. Other treatments may be listed in an appendix. Because these treatments are not universally accepted, these treatments will be given for information only and will not be part of the standard.

5. Recommended elements of a hearing conservation Program

a). Introduction. Regardless of which method is used to predict the effects of Impulsive noise on hearing, the actual effect can be verified by giving routine audiograms to all exposed personnel. It recommended that semi-annual audiograms be given to all personnel routinely exposed to impulse noise with peak levels above 140 dB. In addition, some method for quickly checking for temporary threshold shifts should be established.

b). Semi-annual Audiograms Anyone exposed to impulse above 140 dB should be placed on a hearing conservation program, At a minimum, such a program should establish a baseline hearing threshold level for each exposed individual. After the baseline is established, at least two audiograms per year should be given to that individual. Changes in hearing threshold of 15 decibels or more at any frequency from .5 kHz to 6kHz should be the cause for intervention action.

c). TTS Checks While exposure to impulsive noise is occurring, it is recommended that a quick check for Temporary Threshold Shifts (TTS) in hearing be routinely accomplished.

6) Level at which non-auditory damage should be investigated

a). General At sufficiently high sound pressure levels, injury to parts of the body other than the inner ear becomes a concern. The incidence and severity of such injury increases with sound pressure level, type of waveform and number of exposures. This standard does not provide the relationship of injury and the preceding parameters, but does provide in terms of Peak sound pressure level the evaluation threshold at which non-auditory injury may be of concern. . The standard will not cover the evaluation of exposures above this threshold. However, some possible approaches will be given for information only.

b). Evaluation threshold of non-auditory injury The evaluation threshold of non-auditory injury is set to be a level that is below the true threshold of injury for any reasonable type of impulsive waveform and for a reasonable number of exposures. This level is an unweighted (.01Hz to 10000 Hz) peak of 180 decibels or approximately 20 kPa.

c). Possible models for the evaluation of injury when the evaluation threshold is exceeded. There are established models and procedures for the evaluation of non-auditory injury. These will be given in an appendix of the standard and will be for information only. In addition, the formulation presented in my other paper at this meeting on a possible non-auditory design criteria will probably also be put into this appendix for information only. This formulation is:

For free field waves with a clearly defined A-duration under 10 ms

$$\text{Max peak} = 195\text{ dB} - 10\log(\text{A-Duration}) - 2.5\log(N)$$

And for all other transient waveforms

$$\text{Max peak} = 185\text{ dB} - 2.5\log(N)$$

Where: The max peak is an average with a standard deviation of less than 1 dB

The A-duration is the time in milliseconds that the positive going peak overpressure stays positive without going negative.

For non-freefield waveforms, the Max peak is the greatest overpressure observed during the transient.

N is the number of individual `transients during any day.

It is tempting, however, to try to make this part of the auditory standard. The 10 log t is an equal energy term, matching the survey method. The coefficient 2.5 of the "2.5 log N" term matches the range of 2 to 3 for this coefficient found for the best tradeoff using under-the-muff data (Patterson, et. al., 1997).

7) Peak level for fetal noise exposure The standard will also suggest that pregnant persons should not be exposed to peak levels above a c-weighted peak of 155 after the fifth month of pregnancy.

This recommendation is supported by the study of Gerhardt et al. (Gerhardt, et. al., 1998). Eleven pregnant sheep at a gestation of 127 days were exposed to twenty impulses using a shock tube 4 feet from the sheep. With the sheep removed, peak levels of an average of 169.7 dB were obtained at the position of the fetus. Slight elevations of evoked potential threshold were noted for low-frequency stimuli. Scanning electron microscopy revealed damage to hair cells in the middle and apical turns of the cochlea. Using a hydrophone within the uterus, the differences in attenuation between the air and the uterus varied 2 dB to 20 dB.

The 155 dBC value was derived by two approaches. The first approach assumed during the study that the average attenuation between the air measurements and the fetal head was 11 dB ((2+20)/2). The worst case situation of the fetal head next to the surface of the abdomen would indicate that such hair cell injury could have occurred from a peak 9 dB lower or 161 dBC. Because there is only one experimental point and injury occurred at this point, the threshold of injury is difficult to predict. However it seems reasonable to estimate this point by reducing the peak pressure by at least a factor of 2 (or 6 dB). This results in an estimate of a peak level of 155 dBC.

The second approach is to adjust the current peak limit of 140 dBC by a reasonable estimate of the amount of protection afforded by the abdomen and the lack of middle ear function. As shown in the previous approach, the womb may provide as little as 2 dB of attenuation. The lack of middle ear function results in an attenuation that ranges from 10 to 40 dB through 125 Hz to 2000 Hz (Gerhardt et al., 1992). This would indicate a limiting level from impulses in air could be anywhere from 150 (140+10) dBC to 180 (140+40) dBC. A 150 dBC limit would be a worse case estimate for both frequency and fetal position. Thus, a slightly higher value was considered to be reasonable. The 155 dBC peak limit was the value considered being a reasonable estimate.

The significance of the 155-dBC limit should not be underestimated. It basically means that a pregnant woman after the fifth month should not be using firearms greater than .22 cal.

D. Conclusions: The Standard of which I have outlined is currently a committee draft. It will be circulated for approval in the near future. Undoubtedly there will be some negative votes to resolve and some changes made. The fact that it does not contain the hazard risk curves of many existing procedures may worry some of the committee members. However, I believe that elimination of hazard risk curves that have been based on only one type of impulsive noise will lead to less hearing loss, while at the same time allowing the military to design larger and more energetic weapons. I personally believe that the manner that impulse noise has been handled up to now has been wrong. There is a complex relationship between the type of impulsive noise, the type of hearing protector, training of the users in the use of hearing protection and the motivation of the user of the hearing protection. These later two elements cannot be ignored and can not be predicted by a set of curves. They must be measured and continuously monitored, much as the performance of a weapon system is measured by "live-fire" exercises.

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Performance of Hearing Protectors in Impulse Noise

K. Buck
French German Research Institute
BP 34, 5 rue du Général Cassagnou
68301 Saint-Louis CEDEX
France

Summary

The present paper describes the problems that may occur when hearing protectors, usually designed for industrial noise environments, are used in military impulse noise. The military impulse noise environment is described as well as the different types of passive and active hearing protectors and the used measurement procedures. The different mechanisms that may alter the effectiveness of different types of hearing protectors, as well as the global efficiency when submitted to high level impulse noise, will be shown.

Introduction

The current standard in the industrial community for the evaluation of hearing protectors, uses the threshold of hearing as a reference. This method, called REAT (Real Ear At Threshold), measures the threshold of hearing with and without a protection device, and the difference is defined as the so called IL (Insertion Loss). As no other normalized methods are available, the military community has used the same methods for the evaluation of their protection devices. However, the military noise environment may differ a lot from such found in workshops. Especially the noise of weapons can hardly be compared with noises found in the civilian environment. Weapon noise may expose the soldiers to peak levels as high as 190 dB. If the performance of a protection device is evaluated at threshold, this means, that the found values have to be invariant for an amplitude range of more than 160 dB, (for an amplitude that may vary in a range of 1 to 10^8 or more, if the most powerful weapons are considered). As it is not reasonable, to think that no secondary effects or nonlinearities may be found through such a big range, the performance of hearing protectors, should not be only evaluated at low levels, but also at levels and for signals, that are typical for the military environment. To do this, the evaluation procedures and the associated tools have to be adapted to the high levels to which the devices will be exposed. As each different type of hearing protector may respond in a different way to impulse noise at very high levels, it is important to understand the specificities of the different protecting devices.

Impulse noises in the military environment

The military noise environment is usually not very silent. The rush to higher performance for tanks,

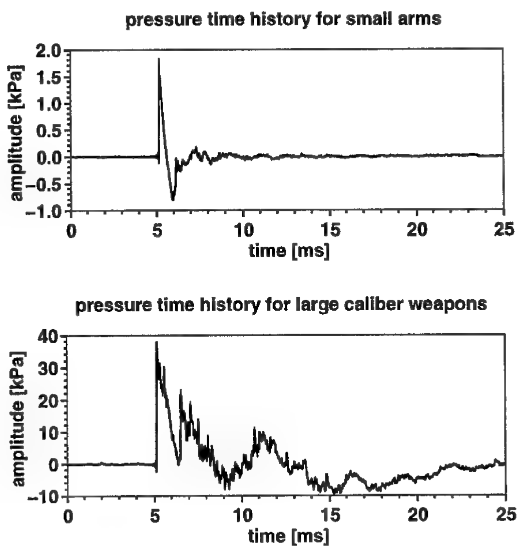

Figure 1 : Typical time pressure histories for small arms (A) and large caliber weapons (B)

airplanes and weapons leads to more noise. The noise level to which the crew members of a tank are exposed is in the range of 110 dBA. Technical staff that has to stay near fighter airplanes is even exposed to higher levels (up to almost 140 dBA).
The impulse noise created by modern weapons, may range from 150 dB peak pressure level with a

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duration of 0.5 ms for handguns, to almost 190 dB and a duration of some milliseconds for howitzers and mortars. In figure 1 two typical pressure time histories due to the firing of weapons are shown. The upper curve (A) shows a small arm's (e.g. rifle or handgun) signature. The maximal pressure of this type of weapon

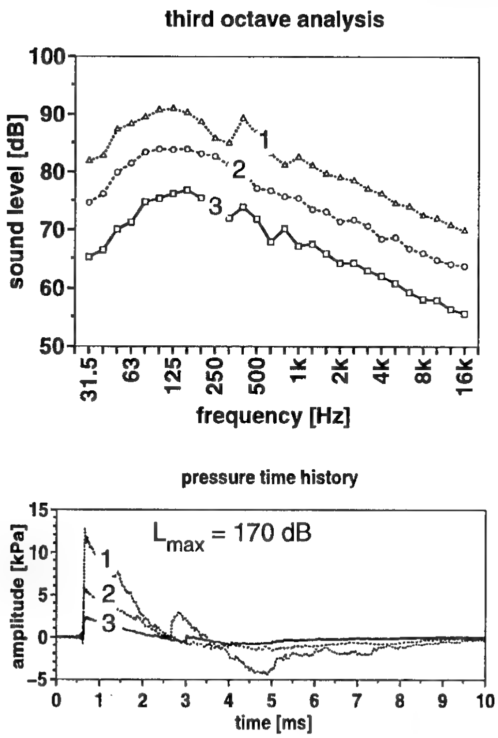


Figure 2 : Third octave analysis for the different weapon noises with the same A-duration (upper graph) and different amplitudes.
The corresponding time signals are drawn in the lower graph

is between 150 dB and 170 dB at the ear of the user. The A-duration of the signature of such weapons is about 0.3 ms to 0.6 ms. In the lower frame (B), the pressure time history of a large caliber weapon is drawn (e.g. howitzer or mortar). For these weapons, the maximal pressure may exceed 180 dB, and the duration is in a range between 2 and 4 ms. The spectral compositions of these noises are displayed in figure 2 and 3. We can see in these figures, how the spectral composition depends on the pressure time history of the signal. Figure 2 shows that, for constant duration and for different amplitudes, only the level of the different components changes but not the envelope of the third octave analysis. For impulse noises having the same peak pressure, but different A-durations (figure 3), the high frequency components of the spectrum stay the same, but the low frequency energy of the spectrum becomes, with growing duration, more important. These figures (2 and 3) show that the spectral

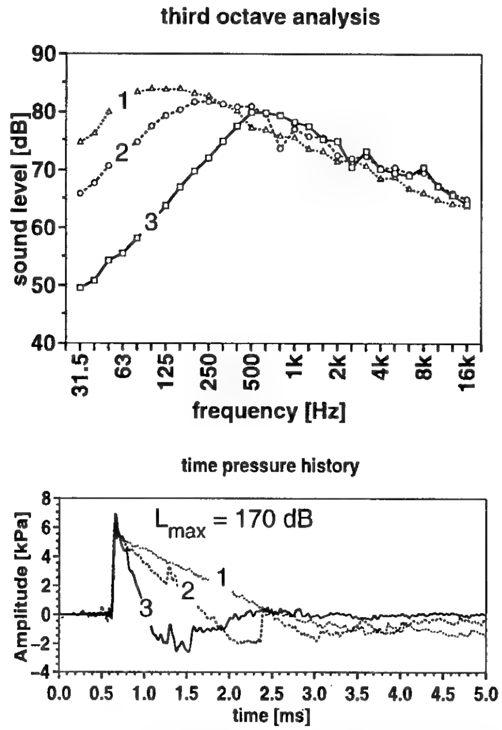


Figure 3 : Third octave analysis for the different weapon noises with the same amplitude (upper graph) and different durations. The corresponding time signals are drawn in the lower graph.

distribution of the energy, for shock waves with identical peak pressures, is the same for all frequencies higher than 1 kHz (if we consider realistic weapon noise) and extends towards the lower frequency bands if the duration of the impulse becomes longer. For waves with a constant duration, change in amplitude only affects the amplitudes of the different spectral components.

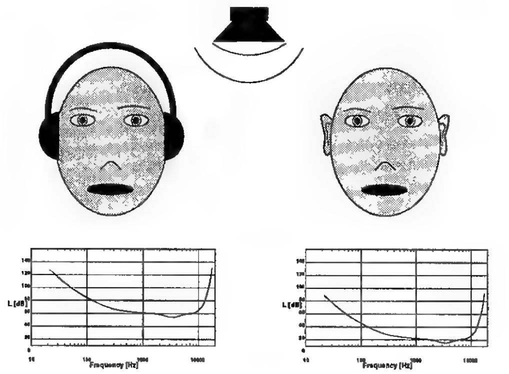
The time pressure histories in the two figures show, that the rarefaction phase of the pressure signals is usually about one third of the maximal overpressure, but its duration may be two to three times longer, and this part of the wave may be very important for the responses of hearing protectors at very high impulse noise levels.

The evaluation method for hearing protectors in impulse noise

The evaluation of hearing protectors for the use in continuous noise is well known, and normalized in different standards. There are mainly two different types of evaluation procedures of hearing protectors :

- subjective methods: the subjective response of human subjects is needed to obtain result,
- objective methods: the result is obtained by physical noise measurements.

Subjective methods:
The best known of the subjective evaluation methods for hearing protectors is the so called REAT (**R**eal **E**ar **A**t **T**hreshold) method. The principle (figure 4) of this



$$IL = L_{Th\ protected} - L_{Th\ unprotected}$$

Figure 4 : Calculation of the insertion loss with the REAT method

method consists in measuring the threshold of hearing of a subject in free sound field with and without a hearing protector. The level difference between the measurement with protected ears, and the measurement of the unprotected ears is defined to be the **I**nsertion **L**oss (IL). This method is widely accepted in the industry. As the behaviour of a hearing protector in 180 dB peak pressure level impulse noise is not the same than in continuous noise at threshold, the REAT method should not be used for the evaluation of material due to work in military impulse noise environments.

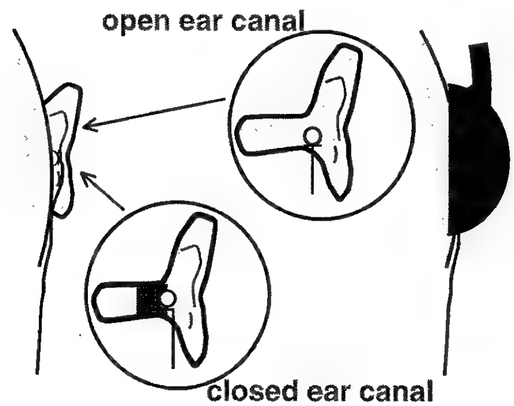
Objective methods:
Objective methods determine the insertion loss by the means of physical measurements. There are two main types:

- the MIRE (**MI**crophone in **R**eal **E**ar) method,
- the method using an ATF (**A**rtificial **T**est **F**ixture) or "artificial head".

The MIRE method consists basically (figure 5) in measuring the pressure at the entrance or inside the ear canal of a human subject. There are different ways how the microphone may be placed in near the entrance of the ear canal:

- placing it with adequate means near the entrance and leaving the ear canal open. This method has the advantage to preserve the input impedance of the ear canal, what might be important for the evaluation of ANR devices.
- fixing the microphone on top of an ear plug which will be inserted. This method is usable for high noise levels because of the protection of the subjects ear by means of the ear plug.

The evaluation of hearing protectors with this method has the advantage of taking into account more



$$IL = L_{unprotected} - L_{protected}$$

Figure 5 : The MIRE method to determine the IL

accurately the soft tissue surrounding the ear and the morphological differences between subjects. However the evaluation of earplug is not possible by means of this method and still, there are ethical problems in exposing human subjects to levels that may damage the hearing organ.

The limitations of use that are found with the MIRE method, are not applicable for artificial heads (ATF), as artificial heads are equipped with ear simulators and a microphone at the place of the drum. ATFs also allow the measurement of ear plugs and measurements with the open ear up to the physical limits of the transducers in the ear. Moreover, as the ear simulator reproduces

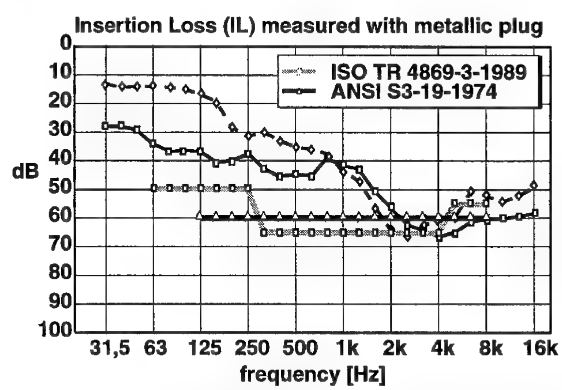


Figure 6 : Acoustic insulation of two commercially available artficial heads compared to the required values of ISO and ANSI

the acoustical impedance at the drum comparable to human data, ANR headsets may be tested without any problems. Although the method is valid for the

evaluation, the artificial heads that are available off the shelf may produce problems in use. Those devices, usually developed for the recording of music or to evaluate communication devices, lack usually of acoustical insulation when the outer ear is blocked. This means, that secondary sound and vibration passes do not allow acceptable attenuation measurements with protection hearing protectors and impulse noise. Figure 6 illustrates this problem. The 2 measured artificial heads were far from fullfilling the requirements of the ANSI or ISO standards, especially in the low frequency range it would not be possible to evaluate any ear plug as the measured attenuation would be the insertion loss of the head and not the insertion loss (~30-40 dB) of the ear plug.

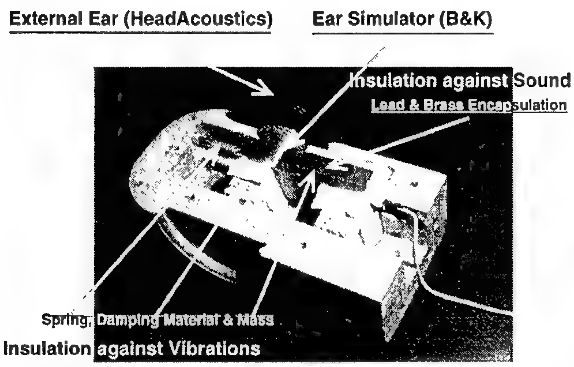


Figure 7 : Acoustically insulated and shock absorbing mount of the measurement elements

As there was no immediate solution to resolve this problem with commercial ATFs, we developped at ISL an artificial head with the aim to fullfill the standards for the whole frequency range. In order to obtain this, the acoustic insulation and shock absorbing mount of the measuring element have been especially looked at. The figure 7 shows the open head and its elements. As far as it was possible, we used elements that were commercialized (e.g. external ear from Head-Acoustics; Ear simulator - B&K). The final product, and its performance (figure 8) were fully satisfactory. The acoustic insulation was more than 60 dB for all frequencies, what complies with the ISO/ANSI requirements.
To obtain the insertion loss of a hearing protector, we proceeded in the same way as already described for the MIRE method (fig 5): two measurements were made, one with and one without the hearing protector; the difference between these measurements being the IL.

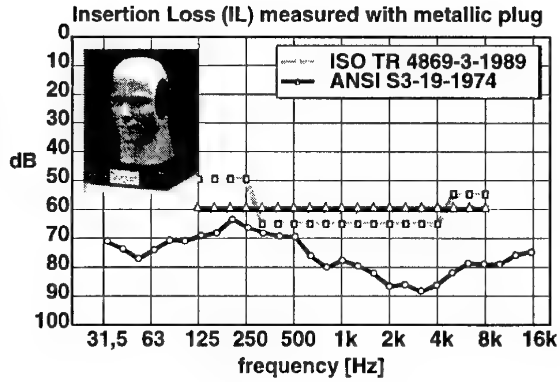


Figure 8 : Acoustically insulated and shock absorbing mount of the measuremet elements

Generation of the impulse noise:
As it is pratically impossible to generate impulse noise with maximum level of 190 dB with loudspeakers, or other electrical devices, there are only two possibilities left:

- shots with real ammunition,
- detonation of explosives.

As real shots are very expensive and involve many personal, we use for our tests explosive charges (Plastit ®) of different weights, being situated at different distances from the artificial head. This technique allows us to have well defined acoustical waves in the free field with peak pressures between 150 dB and 190 dB and different A durations (0.4 - 2 ms). Figure 9 shows how the artifical head and the free field microphone are situated. The distance from the explosive charge is variable, depending on the requirements (signal duration and peak level).

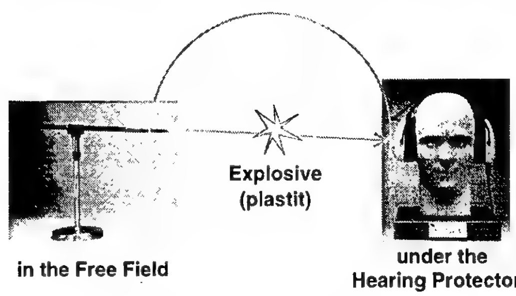


Figure 9 : Setup for a measurement to evaluate hearing protectors with high level impulse noise

The different types of hearing protectors

As far as the hearing protectors are concerned, there are two basic types of protectors:

- Ear muffs:
  This type of hearing protector insulates the ear from outside noise with a barrier shell sealed by a circumaural seal of elastic material to the head,
- Ear plugs:
  In this case the insulation is realised by occluding the external ear canal by means of soft acoustically insulating material.

These two types of hearing protection are shown in the

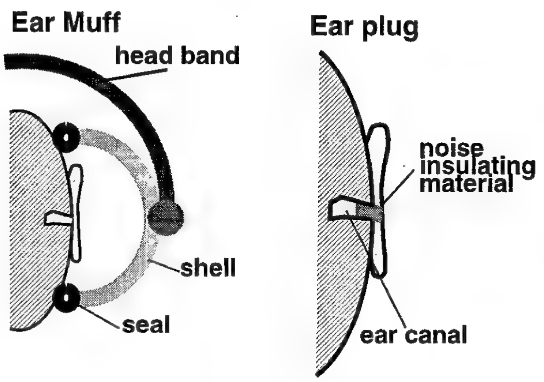


Figure 10 : The two main types of hearing protectors.

figure 10. Depending on the noise and the tasks of the wearer of the protection device, different types have been derived from these basic principles.

Ear muffs: The noise insulation of an ear muff is mainly determined by the following variables:

- the mass of the shell + seal + effective part of the head band,
- the constants of the material of the seal, e.g: density, stiffness, damping ...
- the material constants of the shell, e.g.: density, stiffness, damping ...
- the residual volume underneath the shell and the acoustic damping inside this volume,
- the overall damping of the system, including head band, seal and shell.

Typically, the insulation of an ear muff has to be considered for two frequency ranges where the

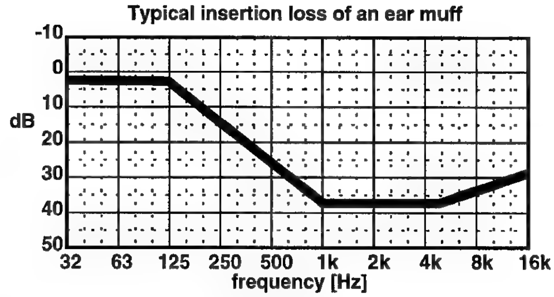


Figure 11 : Typical attenuation of an ear muff

different parameters, enumerated before, govern the attenuation behaviour. Figure 11 shows these different parts. For low frequencies, up to about 1 kHz, an ear muff acts mainly like a low pass filter. The simplified

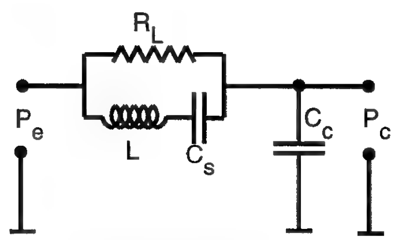


Figure 12 : "very" simplified electrical equivalent of an ear muff for low frequencies

electrical equivalent of the behaviour of the ear muff at low frequencies is shown in the figure 12, where

p_e	corresponds to the pressure outside,
P_c	to the pressure underneath the muff,
L	to the equivalent mass of one earcup,
C_s	to the compliance of the seal,
C_c	to the compliance of the air volume, underneath the cup,
R_L	resistance of the leak in the seal.

We can see in this figure, that the predominent parameter for the low frequency attenuation, is the residual volume under the shell. The bigger this volume (C_c) for constant L,C_s and R_L, the lower will be the residual pressure P_c. The transient phase (about 150 Hz in figure 11) is governed by the mass (L) and the compliance of the seal (C_s) of the protection device. For the frequency range up to 500 Hz the most important parameters are :

- the volume of the hearing protector,
- the mass of the protector,
- the compliance of the circumaural seal,
- the leakage through the circumaural seal.

This means: To get a good insertion loss at low frequencies, we need to design a ear muff with a very big volume, that is very heavy and equipped with a very unflexible but perfectly sealing circumaural seal.
In figure 13, a electrical equivalent of the ear muff for medium frequencies is drawn. This range (1 to 4 kHz) is mainly depending on the material constants of the shell (compliance C_p) and the volume of the shell. Here again, a large ear cup would give a better

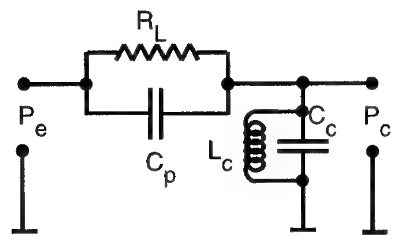


Figure 13 : "very" simplified electrical equivalent of an ear muff for medium frequencies

insulation. However, as bigger cups also might be more flexible, this design approach is not always reasonable, they also will have more weight, and so the user probably will not accept the device. If the inside of the ear muff is not damped, the mass of the air (L_c) and the compliance of the air (C_c) will tend to oscillate. For higher frequencies, as the wavelength becomes comparable to the dimensions of the muff, the inside of the protector may not anymore modeled with lumped parameters. for this case, the most important parameters are the acoustic properties of the material of the ear cup and the parameters of the damping materials inside the shell.

Active Noise Reduction (ANR) ear muffs:

As we have seen before, the low frequency attenuation with ear muffs is usually unsufficient and the parameters that can positively influence this behavior,

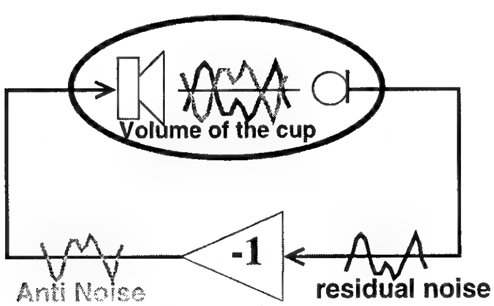


Figure 14 : simplified principel of Active Noise Reduction (ANR)

mass and volume, imped on the ergonomics and on the functionality. A possibility to overcome these limtations, is the addition of an ANR system to the passive protector. The basic principle of that technology (figure 14) is to measure the residual noise in the cavity under the ear muff and to create a noise that is in opposite phase to it. Combining the two noises, results in an attenuation. For stability reasons,

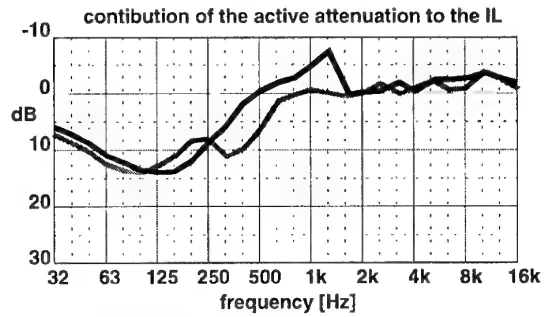


Figure 15 : Attenuation added by an ANR system to the passive Insertion Loss

this principle does not work over the whole frequency range, but only for low frequencies (Figure 15). These devices are very useful in armored cars or helicopters, where the major part of the acoustic energy is delivered in the low frequency range. For weapon noise however, these devices, may be vulnerable due to their electronics involved. This part however will be described in a later paragraph.

Talk through systems:
For working places, that need verbal communication between different people, so called "talk through" hearing protectors have been designed. In this type of

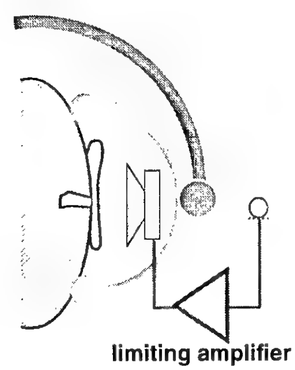


Figure 16 : principle of a "talk through" system

device (figure 16), the external sound is capured by a microphone and fed into the cavity of the hearing protector. To avoid hearing damage due to excessive noise these systems have an amplitude limitation in the amplifier of the telephone inside the cavity. Therefore this protector type may be considered like passive ear muffs for levels that exceed the limitation of the electronic system.

Ear Plugs:
The noise insulation of an ear plug is mainly determined by the following variables:

- the mass of the earplug,
- the constants of the material of the ear plug, e.g: density, stiffness, damping
- the interface between the earplug and the ear canal, e.g. shearstiffness,
- the residual volume under the plug and its acoustic damping

The typical attenuation of an ear plug is shown in figure 17. It is shown, that for a properly fitted ear

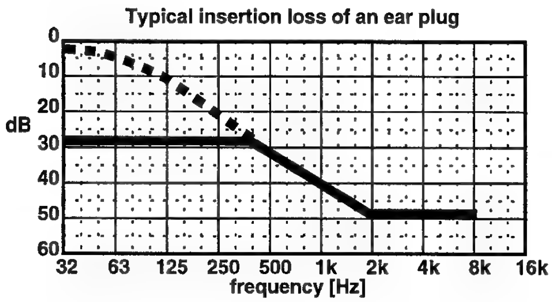
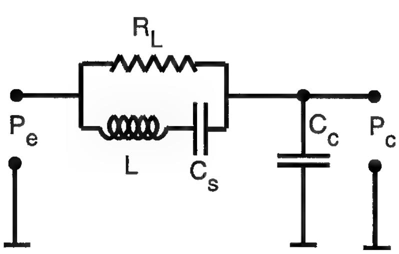


Figure 17 : Typical insertion loss of an ear plug (solid line). The broken line represents the typical IL of a badly fitted plug

plug, the attenuation at low frequencies is already very good. However, if the fitting is not well done, the insertion loss in the low frequency range will be



R_L leakage

L mass of the plug

C_s shear compliance between plug and skin

C_c compliance of the air the residual volume of the ear canal

Figure 18 : "very" simplified electrical equivalent of an ear plug for low frequencies

degraded (dashed line). This effects become understandable, if we look at the simplified electrical equivalent (figure 18). Although it is the same than this of an ear muff, the values of the different components are largely different and affect the behaviour. Especially, as the compliance of the residual volume (C_c) is very small, any leakage will affect the low frequency behaviour very strongly as shown in the figure 17 (difference between well and badly fitted ear plug).

For higher frequencies (>2 kHz), the attenuation of an ear plug is mainly determined by the absorption qualities of the used materials.

Non linear ear plugs:
For many tasks and environments within the military community it is often very important that the soldiers are able to communicate and to hear and interpret the acoustic environment. But these soldiers, also have to be protected against weapon noise, as this could lead to hearing impairement, and so again to communication problems and misinterpretation of the acoustic environment.
In those cases, non linear ear plugs are a good choice. This type of protector only protects against high level noise, and allows almost an unaltered hearing in the

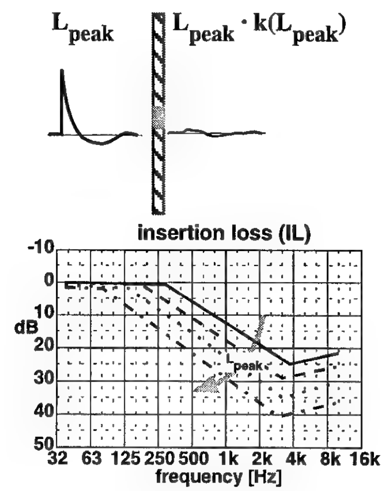


Figure 19 : principle of non linear ear plugs

case of moderate sound fields. The main principle (figure 19) is based on nonlinear acoustic behaviour of small orifices. The acoustic resistance of such orifices is a function of the gasflow through the orifice, and grows with increasing flow. So, for small amplitudes of the noise, the orifice is almost acoustically transparent, whereas for high level impulses, it becomes almost acoustically closed.

Performance in high level impulse noise

Ear muffs:
Ear muffs may be considered to be linear up to a peak pressure level of about 150 dB. Up to this level, the IL measured at threshold may be valid also for impulse noise. For higher levels this is not any more true, because some of the elements described in the

electrical equivalent are no more considered as linear.

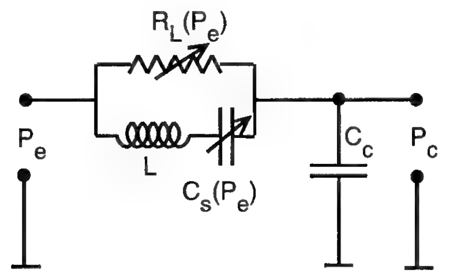


Figure 20 : "very" simplified electrical equivalent of an ear muff for low frequencies for high peak pressures

The value of some of the elements has now to be considered to be a function of the pressure input (pressure in the free sound field). These elements are shown in figure 20. The compliance of the circumaural seal will be modified differently for the overpressure and the rarefaction phases of the pressure signature.

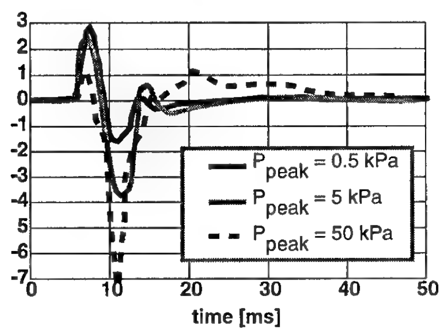


Figure 21 : normalized response under an ear muff for different impulses with the same A duration and different peak pressures.

During the overpressure phase it will become less compliant due to compressibility limits in the material. In the rarefaction phase, the ear cup will be torn away from the head, and that will lead to much higher compliance. The same is true for the leakage (R_L). During the overpressure this acoustical resistance will become bigger and so provide additional isolation, whereas during the rarefaction phase the seal will become less tight and the protection is less effective. These effects can be see in figure 21. The normalized positive peak pressure of the impulse under the ear cup becomes smaller with growing external amplitude, whereas the negative peak becomes more and more important. This leads, if the peak-to-peak amplitude is concerned to less protection with growing free field peak pressures. This decrease can also be observed in figure 22, where the insertion loss of the ear muff for the three different cases is represented. Especially in the low frequency region as well as in the region around 1 to 2 kHz a strong decrease of the

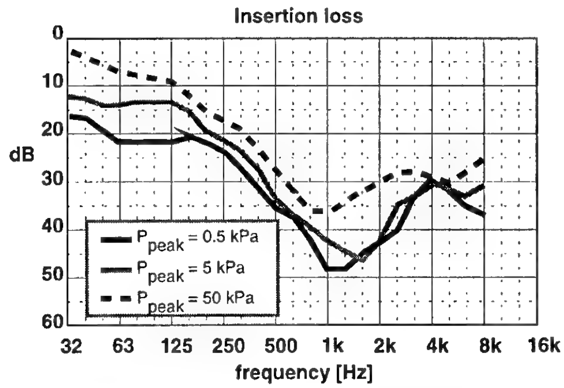


Figure 22 : insertion loss of an ear muff for impulses of the same A duration 2 ms and different Peak pressures

effectiveness (more than 12 dB) of the protector can be observed. These effects depend very much about the configuration of the hearing protectors, and one of the main factors is the force of the head band that holds the protection device. If this force is to small, the amplifying effects during the negative phase of the impulse will appear earlier. The material of the seals also is an important factor. These seals are often made with strongly damped material, in order to get a better insulation in the low frequencies. For very high levels however, these materials cannot expand fast enough, and will allow a bigger leakage than less damped seals.

ANR ear muffs:

For very high levels, as described before, the mechanisms and effects of ANR devices will be the same. However, the contribution of the ANR to the insertion loss as shown in figure 15 will level off at the moment when the needed pressure cannot be any more

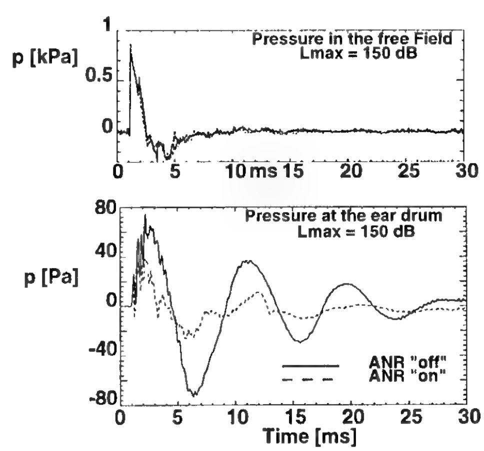


Figure 23 : Effect of ANR on an impulse noise

provided by the loudspeaker of the system. Figure 23 shows how the ANR sytem acts on the impulse under

the ear muff. For this signal, 150 dB peak pressure and 2 ms of A duration, the ANR system is still able to provide some attenuation. At the peak level of 170 dB

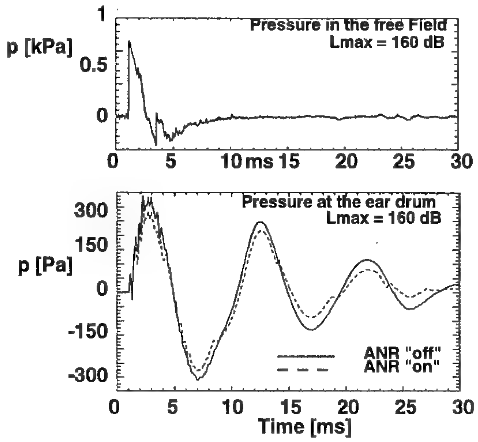


Figure 24 : Effect of ANR on an impulse noise

shown in figure 24 the ANR is not anymore able to contribute some attenuation. As these strong impulse noises, may affect (at least temporarily) the transfer function of the electroacoustic system of the ANR hearing protector it might be possible, that these systems become, for a short time after the impulse, instable.

Talk through ear muffs:
As talk through systems are designed to act like passive ear muffs for levels that are above the saturation level of the amplifier, the same effects as for standard ear muffs will apply. However, if the saturating electronic system is not well designed, undesired noises may arise in the moment of the arrival of an impulse noise.

Ear plugs:
The insertion loss of ear plugs is contrary to that of ear muffs affected only by very high level impulse noises. This can be seen on the figure 25. Although the peak pressure level varies from 150 dB to 190 dB, the variations in the insertion loss does not show variations of more than 5 dB, whereas the IL measured with ear muffs may vary for more than 15 dB. This is mainly due to the fact, that the non linearities that allow the leakeage resistance of the seal to decrease, are not present, as the ear plug is fixed by friction to the ear canal and not by a stiff head band as it is the case with ear muffs. This mechanism tends rather to limit the excursion of the plug in either direction. However, if ear plugs are not well fitted it may well be, that leakage will occur.

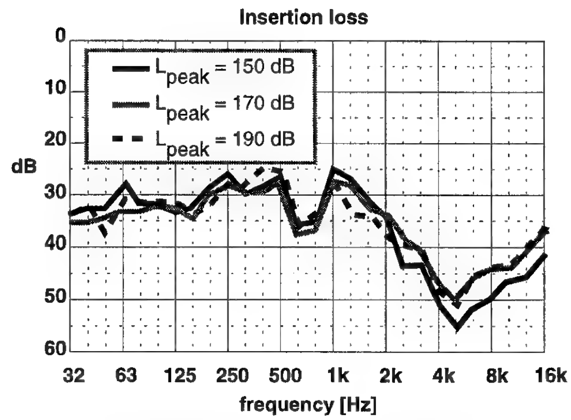


Figure 25 : nsertion loss of an ear plug for impulses of the same A duration 2 ms and different Peak pressures

Non linear ear plugs:
The design of nonlinear earplugs is made in a way, that the insertion loss of the protector should increase substantially with increasing peak pressure of the incident impulse noise. The figure 26 shows very well

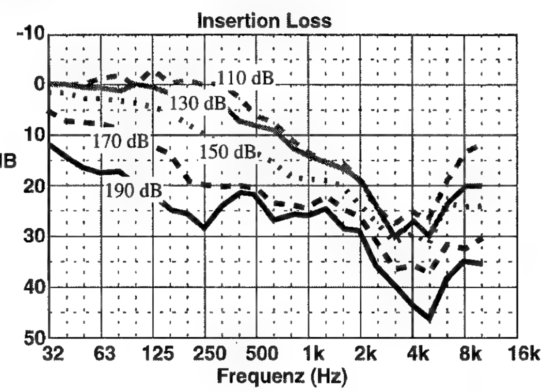


Figure 26 : Insertion Loss of the non linear ear plug developed at the ISL for impulse noise with different peak pressures

the non linearity of this protection device. For signals with a peak pressure level of 110 dB, the Insertion Loss does not exceed 30 dB for any frequency and for spectral components lower than 500 Hz the non linear plug is practically transparent (well fitted standard ear plugs have an attenuation of about 30 dB in this frequency range). For the impulse noise with highest levels (130 dB - 190 dB) the attenuation increases gadually over the whole frequency range. Finally at the peak pressure level of 190 dB, the attenuation over the whole frequency range is almost the same than a good linear earplug. The reduction of the peak pressure of the free field compared to the peak pressure at the microphone of the artificial head follows the same scheme. At a peak pressure level of 110 dB, the reduction of the peak is 8 dB. Passing to higher levels,

this value increases to reach finaly 25 dB for a peak pressure level of 190 dB.

Conclusions

The acoustic environment of the soldier is very different to the noise that will be usually found in the industry. However many of the evaluation standards and measurement procedures are made for this civilian environment. Using these methods would mean to ignore the specificity of the surrounding where the soldier has to work and where unadapted equipment may very well be a reason for operational failure. To avoid this the hearing protection should be evaluated with signals, that really occur, because only these tests allow to be sure that the personnel is protected for all possible cases.

The evaluation of different types of hearing protectors has shown, that the protection that is given for low levels, is not the same than the protection for very high level impulse noise. Especially ear muffs are very dependent of certain design citeria, and so, some very effective features for low levels or continuous noise (e.g. low application force combined with seals made with material having a strong damping) may impede on the protection against high levels. We have seen, that the Insertion Loss may decrease by 15 dB for the highest levels, (compared to the lowest level).

If new types of hearing protectors like ANR systems or "talk through" protectors are evaluated, there is not only the Il to be looked at, but also the behaviour of the electronics when it is driven into saturation. ANR sytems are well able to add extra attenuation to impulse noise of "low" levels, for high levels however, there is always a risk of instabilities.

If no electronic communication requirements are needed, ear plugs may be the first choice for the protection against very high levels of impulse noise. Standard ear plugs may almost be considered as linear protectors for the whole range of levels. Their characteristics change only very little over the whole range of impulse noise levels. However, it is always necessary to have them inserted proprely in the ear canal. If not, the protection capabilities degrade. If verbal communication and acoustic reconaissance of the surrounding area are important, the most interesting way to protect a soldier is non linear ear plugs. These devices are the only protecting devices, that have a better insertion loss for higher levels. They always give the needed protection in the case of a sudden shot, but allow good communication. As these protectors are designed to work only for impulse noise when the user is in a quiet surrounding, they are not suitable to protect against continuous noise. The evaluation of these devices has to be made with impulse noise, because they need noise to work. If these devices are evaluated with standardized methods the results will not reflect their real protection capability in impulse noise.

The protection capability of any type of hearing protector is, to some extent, dependent on the type of signal it is exposed to. It is therefore important to evaluate with signals they will be used for and not with signals that have no relevance.

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COMMUNICATION AND LOCALIZATION WITH HEARING PROTECTORS

Richard L. McKinley
Air Force Research Laboratory
Wright-Patterson Air Force Base, Ohio, USA

ABSTRACT

Hearing protectors are frequently used to preserve hearing when personnel are working in areas of high pulse and/or continuous noise. Speech communication and auditory localization are two important functions of the auditory system, which potentially are impeded when circumaural and/or insert hearing protectors are used. This paper describes the measured effects of hearing protectors on speech communication and auditory localization. The effects on auditory localization include interactions with the visual system and the resulting effects on locating potential objects which may pose a threat to the listener. Implications for military and civilian users of hearing protectors are discussed.

INTRODUCTION

Impulse noise has been a major source of risk for hearing damage. Thousands of military personnel are routinely exposed to small arms, mortar, and/or artillery fire during training. The levels range from approximately 140 dB to over 190 dB. Hearing conservation programs have been established to regulate the exposures of these personnel to both impulse and continuous noise. Most often, the noise level has not been controlled at the source. The normal method of mitigating the noise exposures has been personal hearing protection equipment such as earmuffs and/or earplugs. These types of devices have been optimized over the past forty years in order to provide maximum noise attenuation. However, little, except for a few electronic level dependent earmuffs, has been done to promote speech communication or auditory localization with hearing protectors. Yet speech communication and auditory localization provide significant contact with the environment and are essential factors in safety and ultimately survival in many situations. Hearing protectors affect the auditory signal which reaches the ear. The effect is frequency dependent and often spatially dependent.

Speech communication intelligibility is primarily dependent on the signal-to-noise ratio. For a given noise level, speech intelligibility will increase with increasing speech level until the speech level is approximately 105 dB. If the speech level is increased above 105 dB, the speech signal is distorted in the auditory system and no additional gains are realized in speech intelligibility. One exception is the potential use of an earplug under a communication headset or the use of either earmuffs or earplugs with a public address or sound reinforcement system. In this instance, the speech level and the noise level will be reduced by the hearing protectors. However, the speech level can be increased by using the communication headset or public address system up to a level of 105 dB at the ear (i.e. under the earplug or earmuff), thereby realizing a theoretical gain in the signal-to-noise ratio equal to the attenuation of the hearing protector. This gain is only realized if the quality of the speech can be maintained and produced at these high levels. For an example, if a 25 dB earplug were being used, low distortion, 130 dB (105 dB + 25 dB) speech would need to be produced. This is simple in theory but difficult in practice. Additionally, in a free-field environment, speech communication is aided by spatial content such as experienced at a "cocktail party." This spatial content gives an apparent 2.5 dB improvement in the signal-to-ratio.

A few studies have investigated the effects of hearing protectors on the spatial components of speech, auditory warning signals, and other auditory stimuli. Studies by Atherley & Noble (1970), Noble & Russell (1972), Abel & Armstrong (1993), Vause & Grantham (1999), showed that localization in azimuth is degraded when earmuffs or earplugs are used. The main errors are in front-back or back-front confusions (Vause & Grantham, 1999). Atherley and Noble (1970) found that listeners localizing a 1000 Hz puretone in azimuth made more errors with an earmuff than without. Additionally, listeners using the earmuffs frequently perceived the source as coming from the hemifield contralateral to its actual position. A study

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by Abel and Hay (1996) found a similar effect with a stimulus frequency of 4000 Hz but not with a 500 Hz stimulus. Noble (1981) demonstrated that listeners localize as well in azimuth with earplugs or earmuffs as they do with an open ear when head motion is permitted. He reported slower reaction times with the hearing protectors and reduced capability in localization in elevation. There is a potential safety hazard in the disruption of auditory localization by hearing protectors. Wightman & Kistler (1997) described the physical properties of individual hearing protectors that result in modification of monaural and binaural spectral cues important for auditory localization. Industrial accidents and a few fatalities have been attributed to the inability to hear and/or localize critical audio cues in the immediate environment (Laroche, Ross, Lefebvre, & Larocque, 1995).

These errors are due to the disruptions of the auditory localization cues by the hearing protectors. Oldfield & Parker found in 1984(b) that the interaural time delay was one of the dominant cues for localization in azimuth. However, interaural time delay alone does not allow resolution to a single position. Addition of either head related spectral cues and/or head motion will allow the ambiguity to be resolved. These spectral cues are due to reflections of sound wave by the torso, shoulder, head, and pinnae. Musicant & Butler, 1984, found that the pinnae aid in resolving front-back by producing different spectral cues. Roffler & Butler (1968) also identified these spectral cues to be the primary cue for localization in elevation. Disruption of the shape, volume, etc. of the pinnae would therefore disrupt the formation of these spectral cues and thereby degrade the listener's ability to resolve the source's location in both front-back and up-down directions. However, almost no studies of the effects of hearing protectors on localization have included elevation as part of the study.

The objective of this paper was to describe a series of laboratory experiments which investigate the effects of hearing protectors on speech communication and auditory localization.

METHOD – DATA – DISCUSSION

Each of the studies will be presented individually in the format of method-data-discussion. The subject qualifications for all the studies are described.

Subjects

All volunteer subjects used in the described experiments were recruited from the general civilian population and were paid for their participation. All subjects exhibited pure tone audiograms demonstrating hearing levels equal to or better than 15 dB HL at 125, 250, 500, 1K, 2K, 4K, and 8 KHz. Additionally, they had no abnormalities in their external ear canal and tympanic membrane, and had normal middle ear function as verified by a laboratory research audiologist. Subjects in the auditory/visual interaction experiments also exhibited uncorrected 20/20 visual acuity. The talkers used in the speech intelligibility studies exhibited no strong regional accents. All subjects were native speakers of American English. The number and sex of subjects is described in the experimental design section. All subjects trained for a minimum of four hours on the task, speech intelligibility or localization, before formal data collection was initiated. The subjects also received a bi-weekly audiogram to check for any short-term and/or long term shifts in hearing.

EXPERIMENT SUBGROUP 1 – SPEECH INTELLIGIBILITY

Equipment

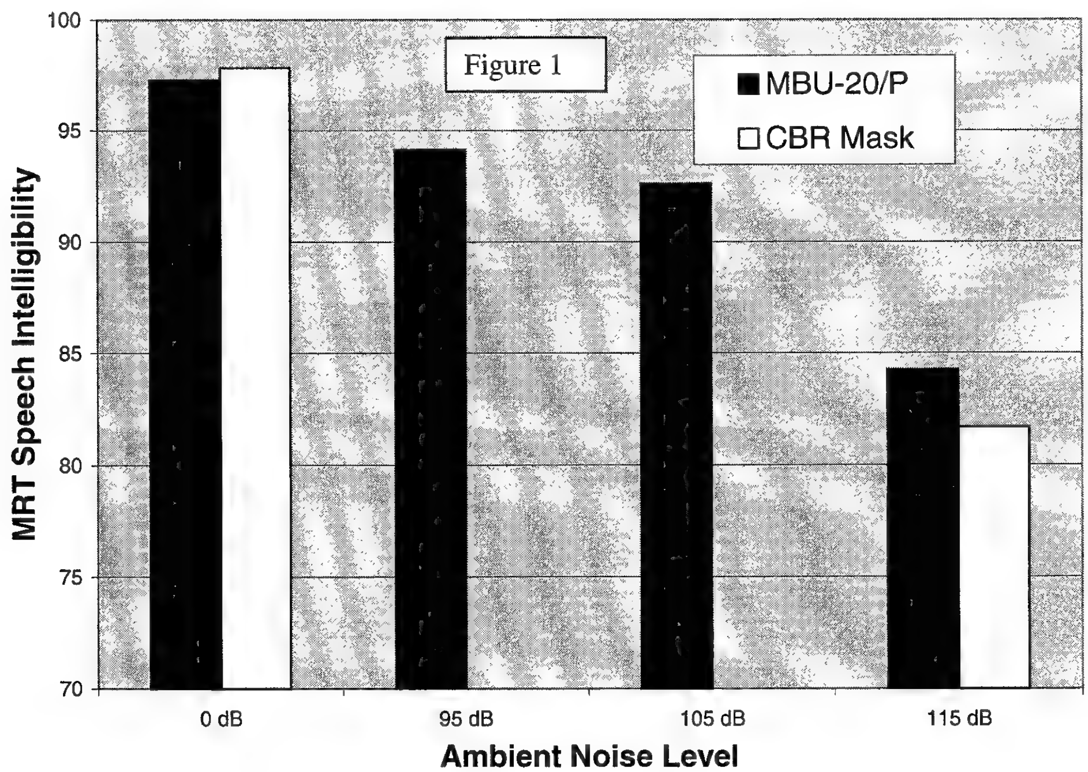
All speech intelligibility experiments were conducted in the Air Force Research Laboratory's (AFRL) Voice Communication Research and Evaluation Facility. This computer based human stimulus and response data facility supports ten simultaneous subjects in an ambient controllable acoustic environment. The calibrated sound field can be varied between a minimum of 45 dB and a maximum of 130 dB. Other AFRL human acoustic facilities are capable of generating sound fields up to 142 dB. The facility gives each talker a VU meter to aid in maintaining consistency of vocal effort during the experiment. Each listener has an individual volume control to adjust the speech to the most comfortable/highest intelligibility listening level.

Experiment A – Speech intelligibility with masks

Design This experiment used five talkers and five listeners, three male and two female. It was a within subjects design, with each subject participating in all experimental conditions. The Modified Rhyme Test (MRT) (ANSI S3.1-1989) was used to measure speech intelligibility. Two different masks were used. The first, the normal oxygen mask, the MBU-20/P, and the second, the chemical-biological-radiation (CBR) mask. The talkers were in a variable ambient noise environment which was an independent variable with four values, 0 dB, 95 dB, 105 dB, and 115 dB. The listeners were in a quiet environment. The CBR mask was measured only at the 0 dB and 115 dB values since it interfered with hearing protection and the subjects' exposures needed to be limited.

Results The results are shown in figure 1. For both masks the speech intelligibility varied with the ambient noise level. At the 115 dB noise level, the speech intelligibility was above 80%.

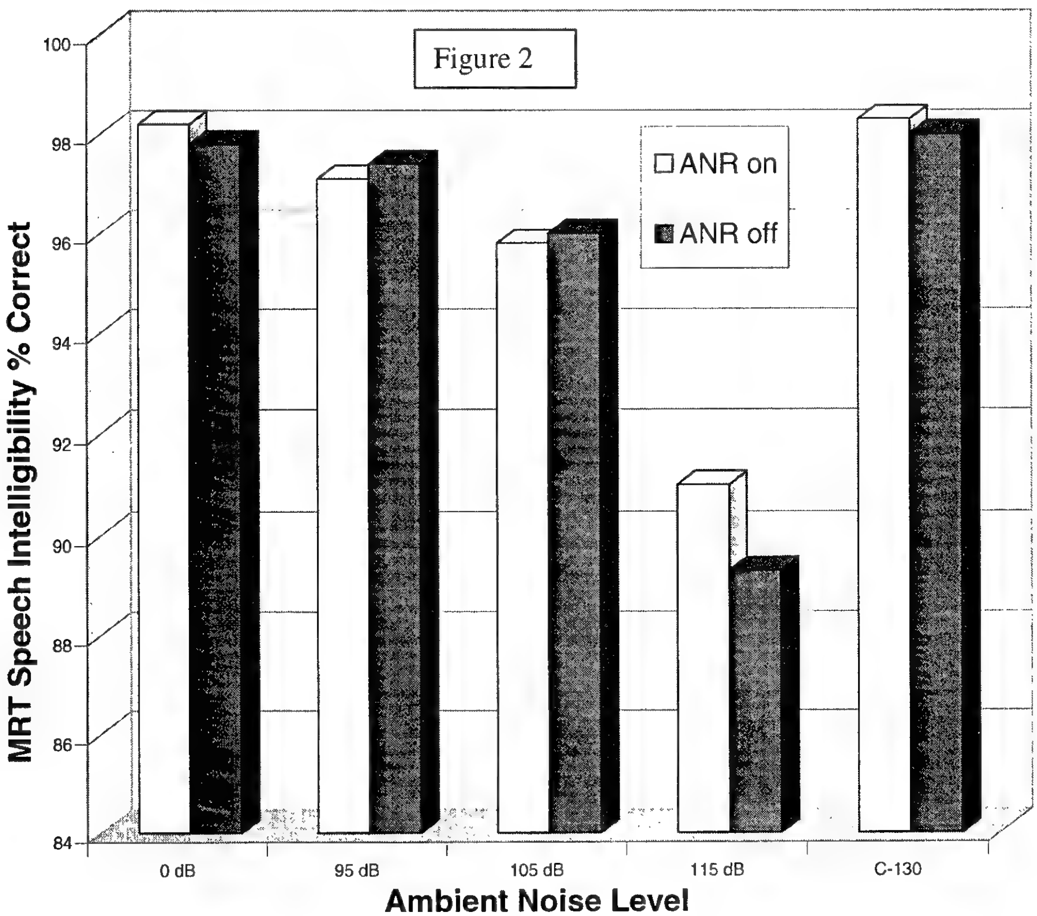
Discussion The intelligibility was controlled by the signal-to-noise ratio at the talker. However, satisfactory communications can be maintained at ambient noise levels up to 115 dB.



Experiment B – Speech intelligibility with Active Noise Reduction (ANR) headsets

Design This experiment used five talkers, three male and two female, and ten listeners, five male and five female. It was a within subjects design, with each subject participating in all experimental conditions. The Modified Rhyme Test (MRT) (ANSI S3.1-1989) was used to measure speech intelligibility. The Bose military PRU-57 ANR headset was operated in both the ANR-on and ANR-off modes. The ANR-on mode achieved an approximate 12 dB reduction in the overall noise level at the ear. The speech levels were approximately equal in both conditions. However, in the ANR-on mode, there is 1-3 dB additive noise in the 1-3 kHz region. The talkers were in a quiet (<45 dB) environment and used H-157 communication headsets including an M-87 noise canceling microphone. The listeners were in a variable ambient noise environment which was an independent variable with four pink noise values (0 dB, 95 dB, 105 dB, and 115 dB) and an additional noise with a C-130 spectrum.

Results The results are shown in figure 2. For ANR conditions the speech intelligibility varied with the ambient noise level. At the 115 dB noise level, the speech intelligibility was above 90% with ANR-on and just below 89% with ANR-off. Similar results were seen with the C-130 noise spectrum.



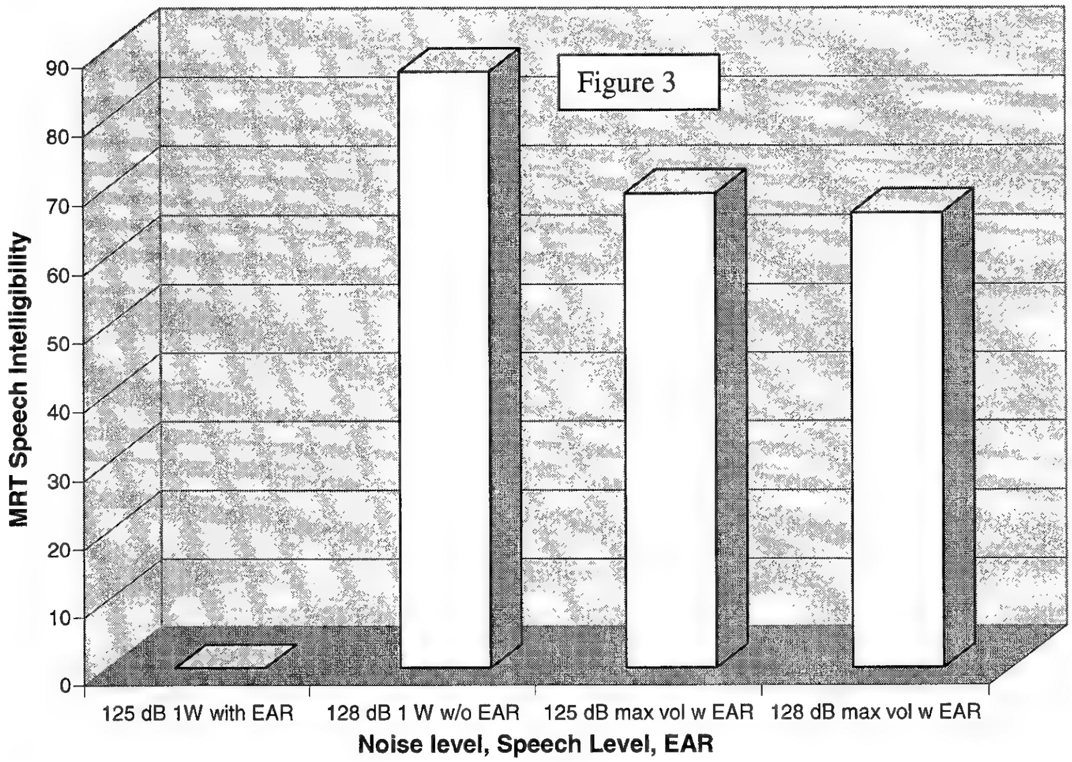
Discussion The intelligibility was controlled by the signal-to-noise ratio at the listener but to a much lesser degree than expected with the ANR headset. Communications were about 10-12% higher than a standard headset, but most of the gain appears to be coming from the improved quality of the speech signal instead of the reduced noise levels produced by the active noise reduction. However, the intelligibility gains are substantial over normal passive noise reduction communication headsets.

Experiment C – Speech intelligibility with EAR earplugs and ANR headset

Design This experiment used five talkers and five listeners, three male and two female. It was a within subjects design, with each subject participating in all experimental conditions. The Modified Rhyme Test (MRT) (ANSI S3.1-1989) was used to measure speech intelligibility. The Bose military PRU-57 ANR headset was installed in a flight helmet (HGU-55/P) and was operated in only the ANR-on mode. The talkers were in a 105 dB pink noise environment and wore flight helmets and oxygen masks with noise canceling microphones. The listeners were in a nearly pink ambient noise environment of 125 dB and 128 dB. Two listening levels were allowed, 1 W total power and maximum volume. The last independent variable was the use of deeply inserted EAR foam earplugs.

Results The results are shown in figure 3. For the 125 dB condition with the EAR plug and with the volume limited to 1 W, the speech was so unintelligible that the subjects could not tell when the speech was presented. The same condition with the volume at maximum resulted in a 69% intelligibility score. When the noise level was raised to 128 dB with the volume still at maximum and using the EAR earplug, the

intelligibility decreased to 66%. However, removing the EAR earplug and limiting the volume to 1 W as in the first condition resulted in an intelligibility of 87%.



Discussion Clearly the audio system was unable to deliver sufficiently intense high quality-low distortion speech to overcome the approximately 35 dB attenuation of the deeply inserted EAR earplugs. Obviously, the intelligibility in noise suffered substantially. However, the ANR headset can deliver satisfactory communication intelligibility at noise levels up to at least 128 dB.

EXPERIMENT SUBGROUP 2 – AURALLY-GUIDED VISUAL SEARCH

Equipment

The aurally-guided visual search experiments D & E were conducted in the Air Force Research Laboratory's Auditory Localization Facility (ALF) at Wright-Patterson Air Force Base, Ohio. ALF consists of a geodesic sphere shown in figure 4 of radius 2.3 m, centered within a cubic anechoic chamber with interior dimensions of 6.7 m with 1.3 m fiberglass wedges. The aluminum struts of the sphere were covered with 2.5 cm acoustic foam in order to minimize reflections. Located at each of the sphere's 277 vertices, spaced approximately 15° apart, was a Bose 4.5" Helical Voice Coil full-range loudspeaker (Model 118038) facing the center of the sphere. As shown in figure 5, mounted 5 cm above the anterior surface of each loudspeaker was a square array of light-emitting diodes (LEDs), each of which emitted a 620 nm wavelength light at a luminance of about 200 mL (Perrott, Cisneros, McKinley, & D'Angelo, 1996).

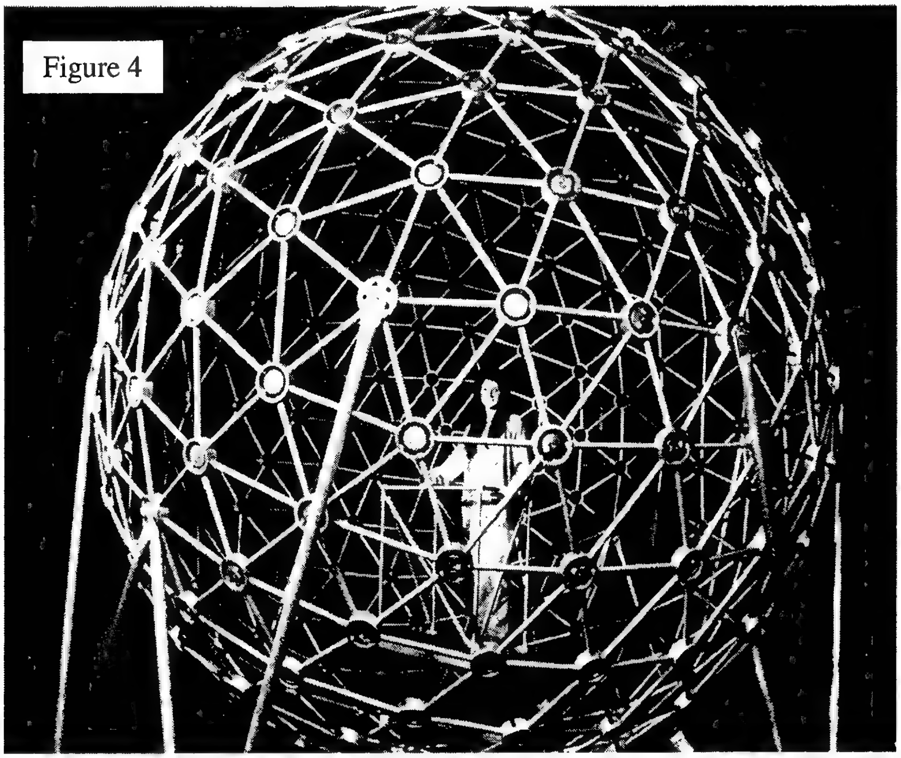
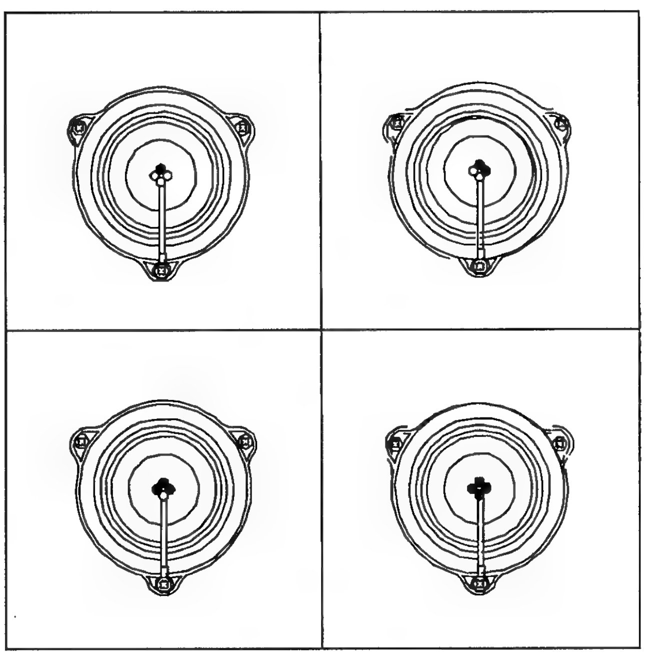


Figure 4

Figure 5



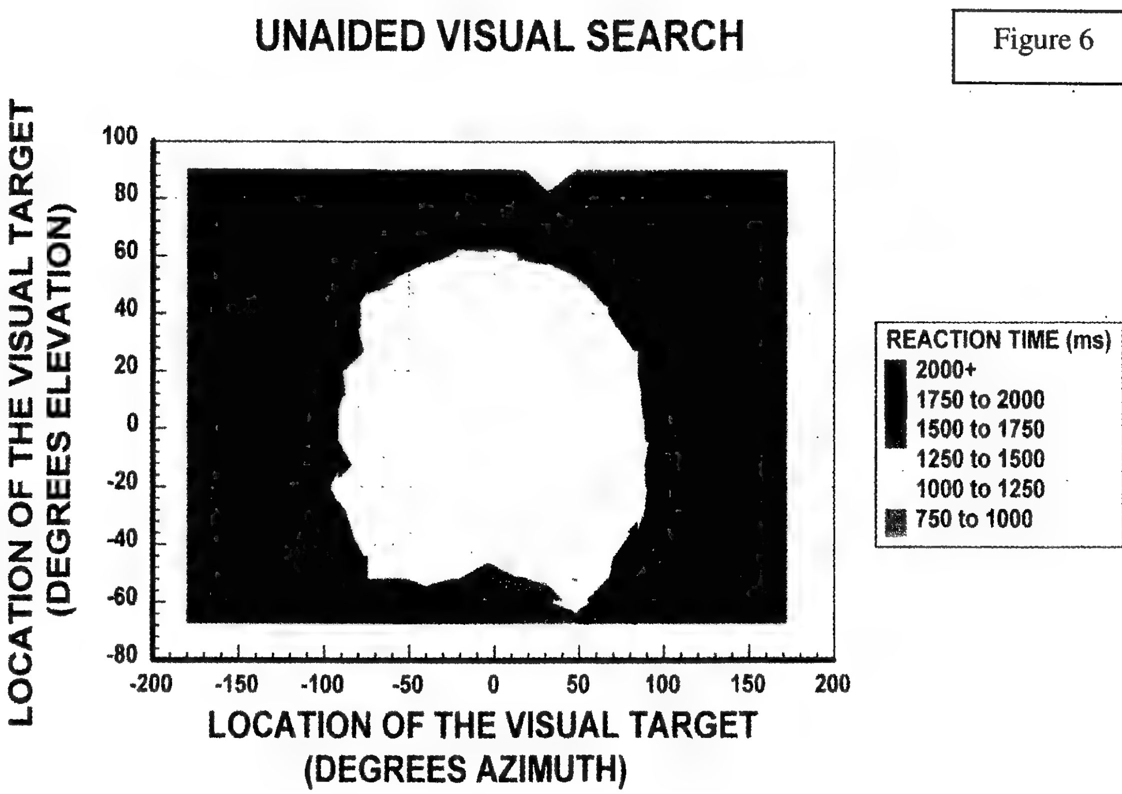
Experiment D – Audio/visual search in a dark field in a real environment

Design A within subjects repeated measures design was used with 528 trials per session and 5 sessions per condition. Six subjects, three male and three female were used in the study. The auditory conditions were no auditory cue, a localized auditory cue via the AFRL–SRL localization cue synthesizer, and auditory cues via the loudspeakers located on the sphere. The auditory stimuli were 250 ms pulsed pink noise with a 50% duty cycle. Therefore the stimuli were on for 250 ms, twice per second. Head motions was measured 60 times per second with a Polhemus 3-Space headtracker. The head motion information was used to update the virtual audio localization cues in real-time.

The subjects fixated at a 0 degree elevation (equator) and 0 degree azimuth location to begin the trial. When ready, the subject determined the number of lights on at the fixation point and responded by pushing one of two buttons indicating the presence of an even or odd number of lights. Immediately the fixation lights were extinguished and a random number of lights came on at a single random speaker location in the sphere. The subject searched the sphere until the single location with lights was located, and then responded odd or even according to the number of lights on at that location. The response time was measured as the time from the fixation response to the correct response to the random stimuli. Errors in response were not counted in the results. However, less than 5% of the responses were incorrect.

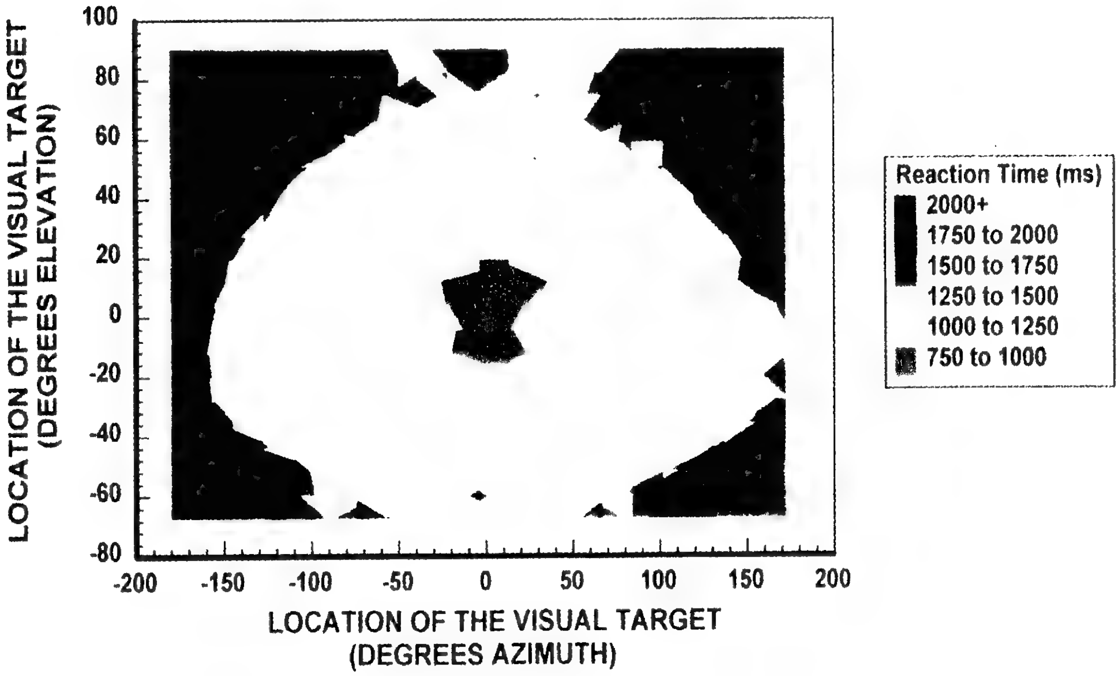
Results Figures 6, 7, and 8 show the response times color-coded in ms for the no audio, virtual headphone audio, and loudspeaker audio conditions respectively. The virtual audio significantly reduces the search time especially at the high and low elevations and in the rear hemi-field. However, the search times are significantly improved in the forward hemi-field. The loudspeaker audio condition displays even faster reaction times, with no times in excess of 1500 ms.

Figure 6



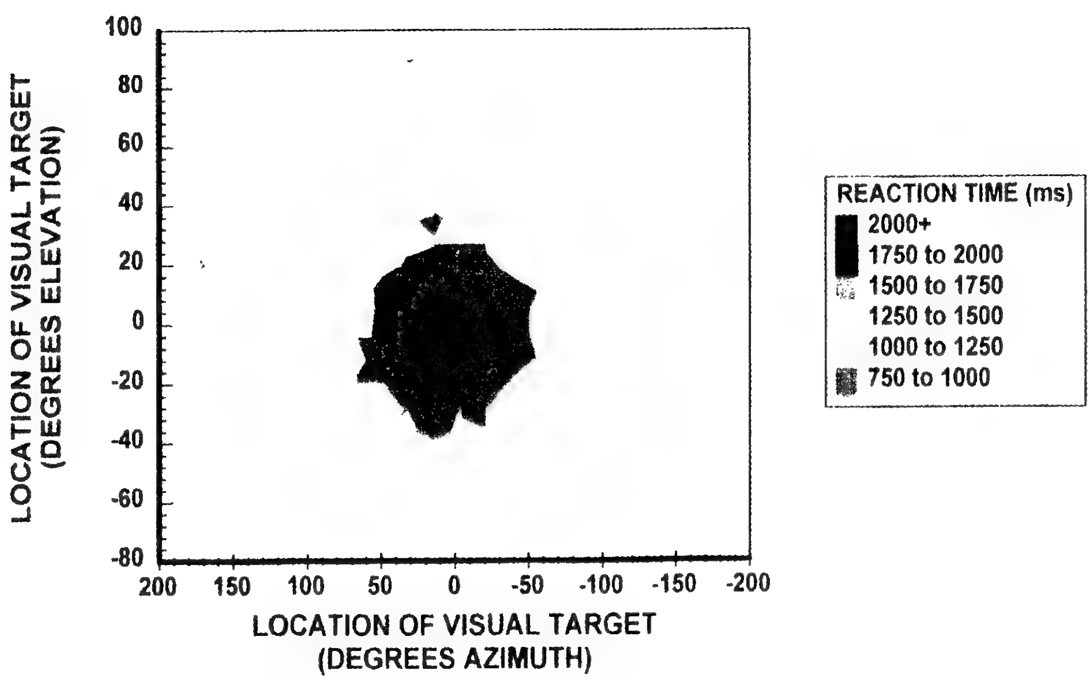
2-D AUDIO AIDED VISUAL SEARCH

Figure 7



LOUDSPEAKER AIDED VISUAL SEARCH

Figure 8

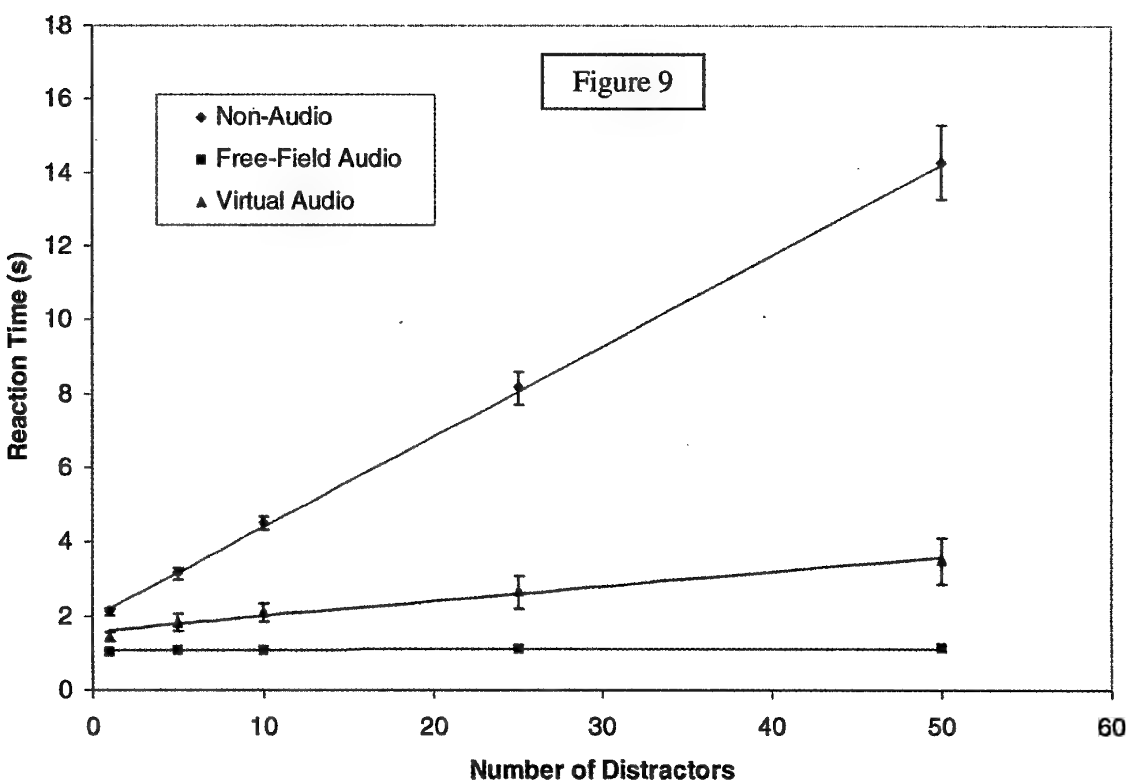


Discussion The results show a clear connection demonstrating that the auditory system can functionally direct the gaze of the visual system. This connection is important from an ecological point of view in that it probably enabled early man to locate prey and avoid becoming prey. The spatial auditory cue enhances the overall performance approximately 50%.

Experiment E – Audio/visual search in a complex visual field in a real environment

Design A within subjects repeated measures design was used with 528 trials per session and five sessions per condition. Five subjects, three male and two female were used in the study. The auditory conditions were no auditory cue, a localized auditory cue via the AFRL–SRL localization cue synthesizer, and via the loudspeakers located on the sphere. The auditory stimuli were 250 ms pulsed pink noise with a 50% duty cycle. Therefore the stimuli were on for 250 ms, twice per second. Head motions and positions were measured 60 times per second with a Polhemus 3-Space headtracker. The head motion information was used to update the virtual audio localization cues in real-time. The visual stimuli were targets of two or four lights in a field of 1 to 50 distractor locations with each distractor location having one or three lights. The simplest case was one target and one distractor. Five different levels of distractors were used, 1, 5, 10, 25, and 50. To begin a trial, the subject fixated at a 0 degree elevation (equator) and 0 degree azimuth location. Once ready, the subject determined the number of lights on at the fixation point and responded by pushing one of two buttons indicating the presence of two or four lights. Immediately the fixation lights were extinguished and a random number of lights came on at two to 50 speaker locations in the sphere. The subject searched the sphere until the one location with two or four lights was located, and then responded two or four according to the number of lights on at that location. The response time was measured as the time from the fixation response to the correct response to the random stimuli. Errors in response were not counted in the results. However, less than 5% of the responses were incorrect.

Results Figure 9 shows the results of the experiment. The visual only search times go up almost linearly with increasing number of distractors. The loudspeaker cue is almost constant at one second. The virtual auditory cue increases only slightly with increasing number of distractors.

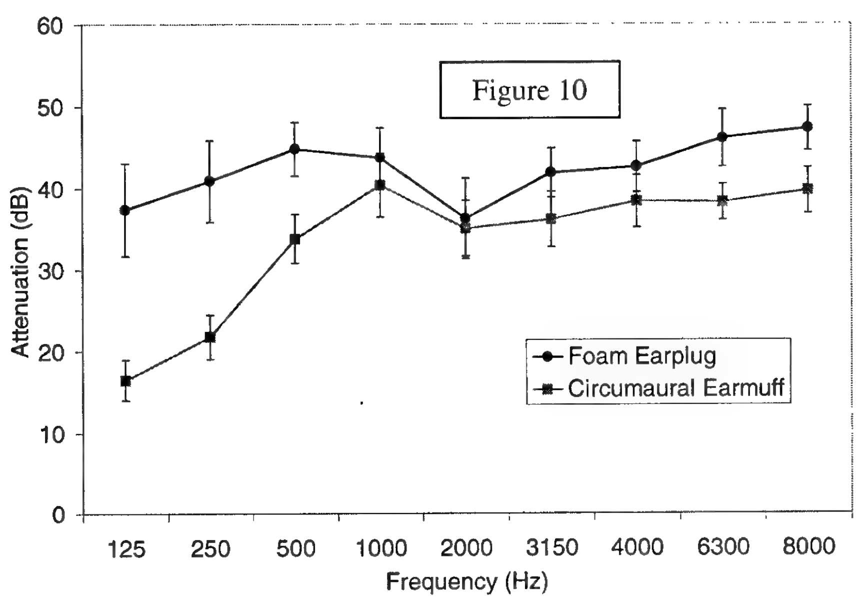


Discussion This experiment clearly shows that spatial auditory cues direct visual gaze in complex as well as simple fields. The fact that the performance with the loudspeaker cue remained constant regardless of the complexity of the visual field is very compelling. It is important to remember that hearing protectors disrupt some of the cues used to localize. Where and how much disruption takes place is of particular importance.

EXPERIMENT SUBGROUP 3 – LOCALIZATION WITH HEARING PROTECTORS

Experiment F – Localization with hearing protectors

Design Two hearing protection devices (HPDs) were employed in this study, the EAR Classic foam earplug and the EAR Model 3000 circumaural earmuff. The nominal attenuation characteristics of these HPDs, as given by the manufacturer, are plotted as a function of frequency in figure 10. Additionally, a non-occluded or no hearing protection condition was included. Localization responses were collected using the God's Eye Localization Pointing (GELP) technique developed by Mark Ericson of the Air Force Research Laboratory and described by Gilkey, et al. 1995. With this method, listeners indicate the perceived location of a sound source by pointing an electromagnetic stylus at the surface of a 20.3-cm-diameter spherical model of auditory space. Two male and four female subjects participated in this experiment. In each of 30 data-collection sessions, 10 for each hearing-protector condition, listeners localized a 750 ms burst of broadband pink noise, presented at 70 dB SPL, from each of the 272 loudspeakers in the sphere. The signal presentation level of 70 dB SPL was chosen in order to be comfortable in the unoccluded listening conditions, but still audible, for all frequency components of the signal, in the occluded conditions. The order in which stimulus locations were sampled was randomized within a session. All experimental data were collected using the GELP technique, described above, with the listener's head fixed by means of a chin rest in order to eliminate head motion as a cue to source location. The ordering of the experimental conditions was randomized. Prior to data collection, all participants were trained extensively on the GELP technique with unoccluded ears and unrestricted head motion. The participants' heads were then fixed using a chin rest, and training continued until performance failed to improve for several consecutive sessions.



Results Figures 11, 12, and 13 show the results of this study. These results point to disturbances in localization performance, in both the horizontal and vertical dimensions. Specifically, the introduction of earplugs or earmuffs occasioned an increase in mean azimuth error on the order of 5°, an increase in mean elevation error of about 15°, and an increase in the percentage of front-back confusions of 24-27%.

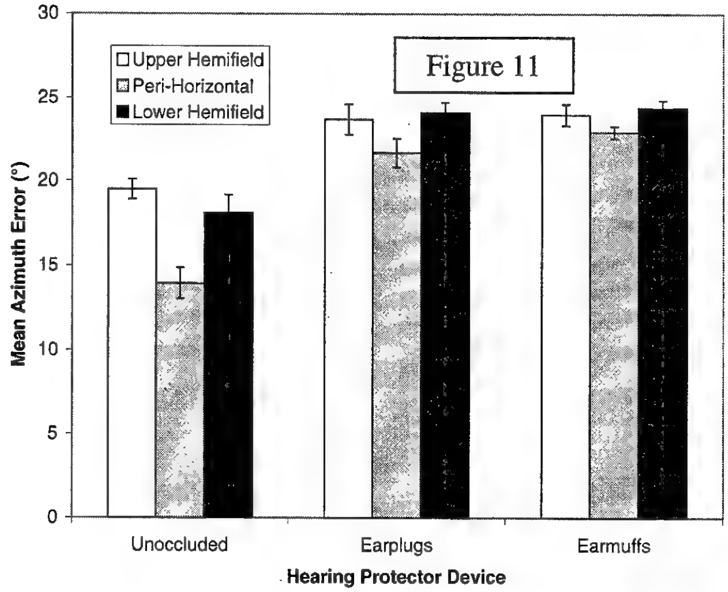


Figure 11
Upper Hemifield
Peri-Horizontal
Lower Hemifield
Mean Azimuth Error (°)
30
25
20
15
10
5
0
Unoccluded
Earplugs
Earmuffs
Hearing Protector Device

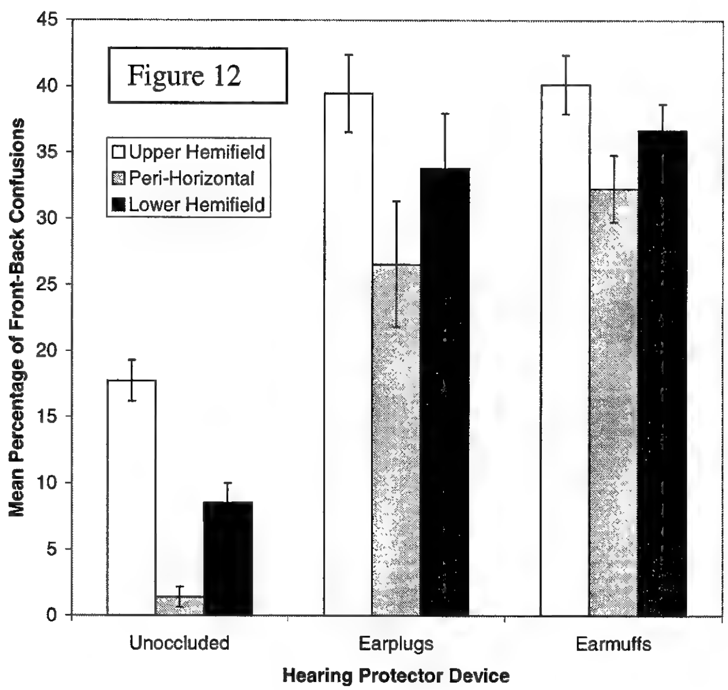
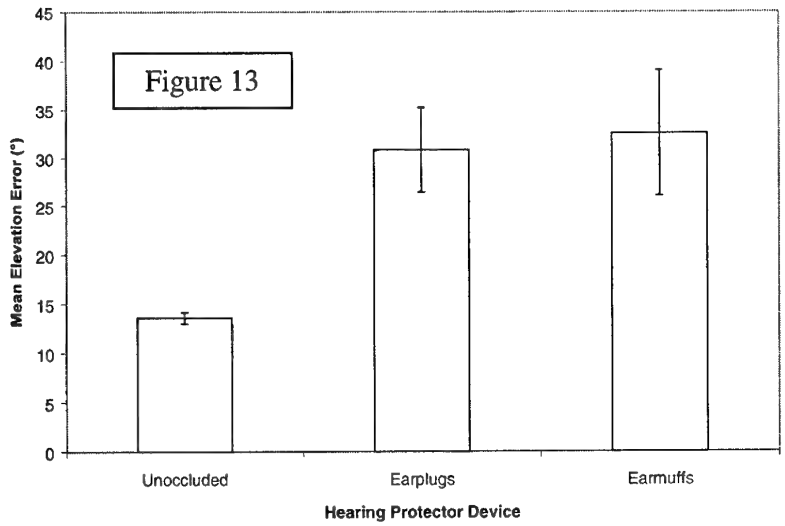


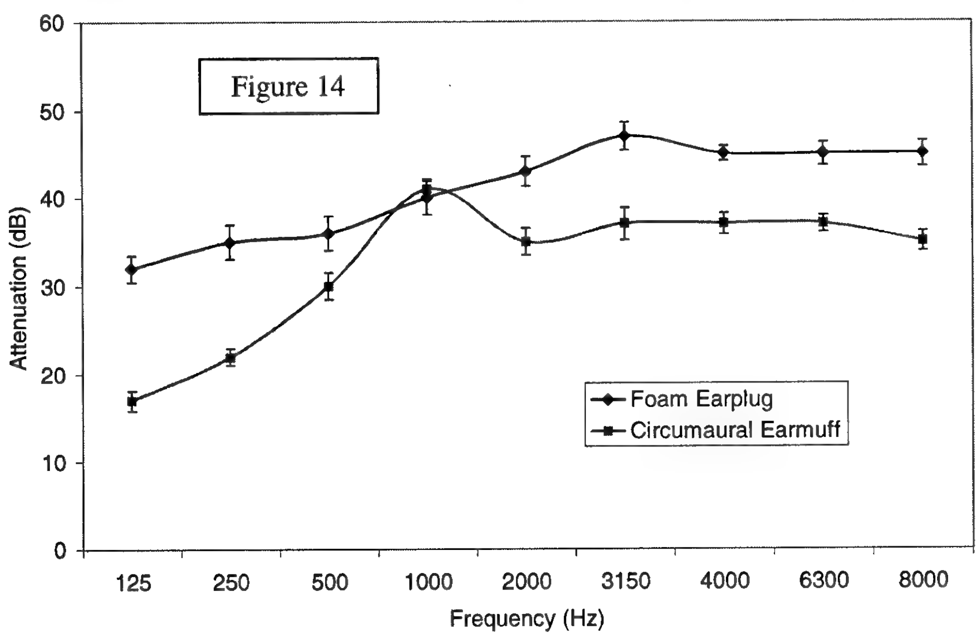
Figure 12
Upper Hemifield
Peri-Horizontal
Lower Hemifield
Mean Percentage of Front-Back Confusions
45
40
35
30
25
20
15
10
5
0
Unoccluded
Earplugs
Earmuffs
Hearing Protector Device



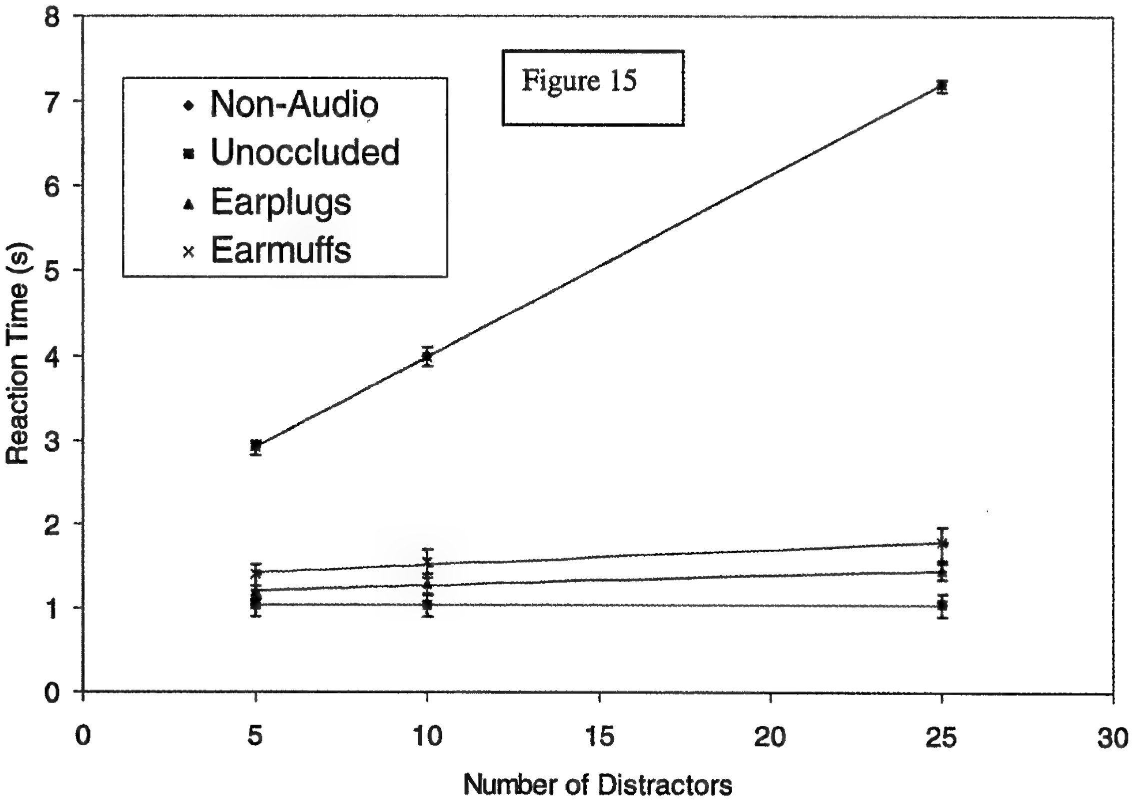
Discussion Localization in both azimuth and elevation are degraded by either earmuffs or earplugs when there is no head motion. This performance degradation is most likely due to the disruption of the spectral cues and the loss of head motion to resolve interaural time delay ambiguity. The performance losses when hearing protectors are worn has many occupational safety implications for both civilian and military users of hearing protectors.

Experiment G – Aurally-guided visual search with distractors and hearing protectors

Design - The EAR Classic foam earplug and the Tasco Sound Shield circumaural earmuff were used in this study. The frequency-dependent attenuation of these devices was measured using the real-ear method (ANSI S12.6-1984), and is depicted graphically in Figure 14. Three subjects, two male and one female, were used in this study. Each had participated in the prior visual search with distractor study describes as experiment E. The same procedures were used in this experiment that were described in experiment E, with the exception that the number of distractors was limited to 5, 10, or 25. The subjects were asked to perform the task with no audio, audio with no hearing protector, audio with the earplug, and audio with the earmuff.



Results The results of this study indicate, as in experiment E, that the visual only search time increases linearly with number of distractors, while the unoccluded search times are constant at about 1 second regardless of the number of distractors. There is only a small effect of the hearing protector, as can be seen by the shallow slope in figure 15.



Discussion The results could be construed as encouraging due to the small (a few 100's of ms) degradation of reaction time in locating the source. But care should be employed. These results were obtained in a laboratory setting with no other noise sources and with substantial visual feedback from the lights. Additional experiments need to be performed investigating the practical auditory localization performance with hearing protectors in a robust visual and acoustic environment.

SUMMARY

This series of experiments has described the impact of hearing protectors, both earplugs and earmuffs, on speech communication capability and on auditory localization. The effects on speech communication are largely negative unless an intense, low distortion, speech signal can be produced at the ear. Clearly this is an area where additional work in developing high-power earphones could benefit a large number of users. Additionally, ANR headsets can improve speech communication capability, but not to the extent that would be predicted from their improved attenuation. This is another area requiring additional research and development. Auditory localization is an inherent part of almost everyone's daily life, improving safety and promoting efficiency. Yet earmuffs and earplugs in some situations seem to seriously degrade localization performance while in others there is little change. This ability to localize acoustic sources is of vital importance in many environments, such as the military, law enforcement, fire fighting, and construction. Once again, additional study is required to resolve the practical issues in this very important area.

ACKNOWLEDGMENTS

The author would like to thank his co-authors and collaborators on previous papers for their hard work and tireless contributions on the many individual experiments that are synopsized in this paper. Specifically Robert Bolia, William D'Angelo, Mark Ericson, David Perrott, W. Todd Nelson, and Charles Nixon.

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Individual Susceptibility to NIHL and New Perspective in Treatment of Acute Noise Trauma

A.L. Dancer
French-German Research Institute of Saint-Louis
BP 34, 5 rue du Gal. Cassagnou
68301 Saint-Louis Cedex
France

Summary

There would be great interest in finding a test which predicts individual susceptibility to permanent threshold shift. Such test would allow identification of people who are most likely to suffer hearing damage in high noise areas and thereby reduce the number of people presenting NIHL.

Considering the consequences of NIHL for the health of the soldiers, the cost of the treatments, the operational and compensation costs induced by NIHL, it is necessary to assess the actual efficiency of the present medical treatments of the acoustic trauma. Preliminary results indicate that some treatments speed up the recovery and correspond to lower threshold shifts and smaller morphological damages. Moreover, experiments are in progress to assess the interest of new treatments applied directly to the inner ear.

Individual Susceptibility to NIHL

1. Introduction

It has long been agreed that there would be great interest in finding a test which predicts individual susceptibility to permanent threshold shift (PTS). Thirty–five years ago, Ward [1] analyzed about 20 proposed tests of individual susceptibility, and found none of them good enough to be useful. Since that time, many other publications on this subject have appeared. Most of the procedures were described by Howell [2] and Buck and Franke [3].

The proposed tests can be divided into two major groups, nonauditory and auditory.

2. Nonauditory tests

Bonaccorsi [4] showed, in men and guinea pigs, that a correlation exists between the concentration of melanin in the stria vascularis and susceptibility to noise. Because the concentration of melanin in the iris of the eye is positively correlated with the concentration in the stria vascularis, it follows that dark eyes are correlated with low noise susceptibility.

It has also been proposed that there is a correlation between general health condition and susceptibility. Different studies [5,6] indicate that good cardiovascular function (i.e., low blood viscosity, low rate of blood platelets aggregate, low rate of cholesterol…) decreases the risk of hearing loss.

Overall, however, the relationship between nonauditory factors and susceptibility is sufficiently weak that they do not seem to offer a basis for an effective susceptibility test.

3. Auditory tests

There are a very large number of proposed tests, almost all of them using some procedure to determine the sensitivity to temporary threshold shift (TTS).

Carhart [7] proposed the "Threshold of Distorsion Test" as an index of susceptibility to TTS. This test used the level at which pure tone nonlinear combination tones could be heard. The "Threshold of Octave Masking Effect" proposed by Humes et al. [8] is based on a similar principle. The "Loudness Discrimination Index", which is based on recruitment (usually observed after a subject is exposed to intense noise), was proposed as an early indicator for TTS [9]. Pederson [10,11] showed that changes in the cochlea due to intense noise alter the slope of the temporal integration function. Thus, Humes [12] proposed that "Brief Tone Audiometry" might be an indicator of susceptibility. Humes [12] also proposed that "Speech Discrimination in Noise" might be used to detect "fragile" ears because frequency integration in the ear might be affected long before any TTS could be detected.

Some authors tried to establish a correlation between the threshold of audibility and the susceptibility to noise [13]. In normal hearing subjects, thresholds are partly determined by the performance of the transfer function of the outer and the middle ears. Therefore, low thresholds could indicate that a large amount of acoustic energy is transmitted to the inner ear [14]. Measurement of the "Middle-Ear Acoustic Reflex", which modulates the transmission of the acoustic energy to the inner ear, has also been suggested as a test of susceptibility [15]. It has been proposed that reflex latency, rise time and fall time could give an indication of sensitivity to TTS. On another hand, as medial olivocochlear efferents connected to the outer hair cells might protect the cochlea against the damaging effects of intense sound exposure [16, 17], the possibility to assess the interindividual susceptibility from the measurement of the "Inner-Ear Acoustic Reflex(es)" when stimulating the ipsilateral and/or the contralateral ear exists, even if controversial [18].

All the auditory tests purport to predict individual susceptibility to TTS, but not to PTS. In fact, most of the tests deals with TTS in humans, and there is no ethical

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way to induce a PTS in humans for experimental purposes. So the problem for all tests is that there must be a correlation between sensitivity to TTS and sensitivity to PTS if they are to have any practical value.
Temkin [19] in 1933, first stated the hypothesis that there should be some relationship between TTS and PTS. In the intervening years, discussion has gone on and there is still no definite answer as to whether this relationship exists or not. Burns and Robinson [20] measured the PTS acquired during a worker's previous employment and compared it to the TTS acquired during one working day. They reported that the group of workers which showed a lower initial hearing sensitivity developed less TTS at the end of the working day. They also concluded "that a higher susceptibility to TTS tends to be associated with higher susceptibility to occupational hearing loss, and vice versa". However, there is considerable uncertainty with respect to the hearing thresholds before the work experience, which makes it difficult to interpret these findings unequivocally. Using the data of Richartz [21], Kraak [22,23] reported a close relationship between TTS integrated over time (ITTS) and PTS. This approach correlates the growth and the recovery of ITTS for a four hour exposure with the PTS due to about one year exposure to the same noise. Although there are some methodological questions, this method shows a surprisingly good correlation between TTS and PTS. Kryter et al. [24] postulated that the TTS observed after one working day should approximate the amount of PTS after ten years work in the same environment. However, these data are mean data for groups and are not applicable to the prediction of individual susceptibility. Jerger and Carhart [25] exposed subjects to 3 kHz tones at 100 dB for 60 seconds and then measured the time it took threshold at 4.5 kHz to return within 20 and 10 dB of pre-exposure levels. The subjects then took a course on jet-engine maintenance where they were regularly subjected to intense noise exposure. Eight weeks after the exposure, PTS was measured. Their results suggest that subjects with a longer recovery time for TTS are more susceptible to PTS. Although there is a trend in their data, the large scatter shows that recovery time is not highly correlated with susceptibility to PTS. Pfander [26] did a study in which 100 soldiers were exposed to three different types of noise (two white noises and gunshots). The five soldiers who showed the slowest recovery from the gunshot also showed PTS at the end of the shooting training. Therefore, he suggested that the recovery time or TTS might be the factor characterizing susceptibility to noise.
The foregoing tests show some relationship between TTS (or related factors) and PTS. Unfortunately, for the most part they were designed to show the correlation for groups, rather than for individuals. It is possible that a test of susceptibility to PTS based on TTS measures may also work very well for individuals. The literature gives no direct answer to this issue, but rather a lot of inconsistencies. Therefore, some authors [3] decided to evaluate whether it was possible to find some correlation between TTS (or related parameters) and susceptibility to PTS for at least one case.
Because of ethical problems, these experiments were performed on animals (guinea pigs). Animals were exposed to a 1/3 octave band noise of moderate level and TTS of about 25 dB were measured (phase I). One week later (after complete recovery), the same animals were exposed to the same noise at a much higher level. PTS were produced and measured up to 40-60 days post-exposure (Phase II). The essentially low correlation between PTS and TTS at the individual level seem to indicate that there are different mechanisms involved (i.e., maximum TTS appears one octave higher than the noise stimulus, but maximum PTS is measured at the center frequency of the noise, meaning that TTS is induced in a different part of the cochlea than PTS). TTS could be mainly due to metabolic depletion or neurotoxicity (vacuolization at the base of the inner hair cells), PTS could be the result of structural modification or destruction of hair cells. This distinction between the metabolic and the mechanical damages is especially relevant to the weapon noises: acute acoustic trauma and PTS may occur following a single exposure to an impulse (mechanical origin). Then, susceptibility to PTS should be tested using methods which are more directly related to the mechanical origin of the PTS. Unfortunately, this means that any test which is perfectly reversible (i.e., a test inducing a TTS of metabolic origin) might not give enough information about PTS.

4. Discussion

It is also essential to stress that the individual susceptibility to noise is probably not the same as a function of age and health condition of the subjects. Somebody who is rated as resistant to noise could, under unpredictable conditions (having a cold, using medicaments...), become especially susceptible. Therefore, it would be hazardous to rate once and for all the auditory susceptibility of any subject.
Very recently a survey performed by Job et al. [27] on 1208 young recruits showed that the harmful effect of noise exposure (PTS, tinnitus) was strongly dependent on the presence of repeated episodes of otitis media in infancy or childhood (even when no sequelae was observable during the otoscopic examination at the time of the survey). This study indicates that a test for individual susceptibility to NIHL could be looked for in other directions than the usual relationships between TTS and PTS.

Treatment of Acute Noise Trauma

1. Introduction

In some countries (France, Germany...) all soldiers suffering acute acoustic trauma receive a medical treatment at the hospital. In France, for the three years 1993, 1994 and 1995, 1,796 soldiers have been treated in

the ENT departments of the military hospitals (total number of days of hospitalization: 7,974). In 1996, 966 cases of acoustic trauma have been reported and treated at a medical cost of 4 million dollar. In Germany, the cost of those treatments is 2.5 million dollar a year. In other countries (United Kingdom, USA...), the soldiers in the same situation are not treated (they are only withdrawn from hazardous noise exposure). However, the acoustic trauma is responsible for many other expenses:

- in all countries, following an acoustic trauma the soldiers are temporarily retired from active service. Then, if they retain large permanent hearing losses they can be definitively withdrawn from front line service. For specialized personnel large formation and training expenses may be definitively wasted,
- in the past 50 years or so, many acoustic trauma went untreated (the actual efficiency of the treatments is a matter of controversy [28], see below). Therefore, in all countries huge compensations are paid each year to the veterans for hearing loss as a primary disability. In the USA, 291.6 million dollar have been distributed in 1999 to 56,792 veterans [29]. In France, the annual cost of the compensations for Noise-Induced-Hearing-Loss (NIHL) is evaluated to 60 million dollar. In Belgium, about two thirds of the 6 million dollar paid yearly to the veterans for all kinds of disabilities correspond to NIHL. Moreover, the acoustic trauma represents the first cause of morbidity in the military during peace time!

Considering:

- the important consequences of NIHL for the health of the soldiers,
- the cost of the medical treatments of the acoustic trauma (in some countries),
- the huge operational and compensation costs induced by NIHL (in all countries),

it is necessary : (i) to know whether the present medical treatments of the acoustic trauma are relevant and must continue to be prescribed in order to advice, or not, to use similar treatments in the other NATO countries, (ii) to determine the most efficient treatment (if any), (iii) to look for new treatments.

Given the difficulties to assess the actual efficiency of the medical treatments of the acoustic trauma in man (ignorance of the pre-exposure hearing condition, ignorance of the noise exposure parameters, use of different treatments, various implementation delays of those treatments, difficulties to differentiate between the normal physiological recovery and the medical assisted recovery, impossibility to perform morphological observations of the sensory organ, ethical problems prohibiting the use of control groups...), the best approach is to use animal experimentation. Animal experimentation allows to study on a statistical basis the functional and the morphological aspects of hearing recovery (and hence the efficiency of such or such treatment) on treated and on untreated groups of animals (controls).

2. Hearing damage from noise

Intense sound stimulation results in various structural changes leading to functional auditory impairment. It is well known that intense sound exposure induces two major types of damage : (i) injuries occurring first in the first row of outer hair cells (OHC), then in the inner hair cells (IHC), and subsequently in the second and third rows of OHC [30], and (ii) massive destruction of the dendrites of the primary auditory neurons below the IHC [31,32,33]. It has been demonstrated that after acoustic trauma, the acute hearing losses are due both to hair cell injuries and to dendrite damage [34]. Synaptic repair can occur in 5 days [35], but most hair cell damage remains which is probably responsible for the long-term threshold shifts. It has also been demonstrated that dendrite damage could be prevented by perfusing a glutamate antagonist [35], or a dopaminergic agonist [34], into the cochlea during the noise exposure. However, it is essential to find *curative* drugs to treat patients who underwent acoustic trauma and to address both the hair cell injuries and the dendrite damage.

3. Experiment

The actual efficiency of the classical medical treatments of the acoustic trauma was assessed by using a well-standardized animal study by d'Aldin et al. [36]. The results are related to the effect of the most widely used medical treatments. The effects of acoustic trauma are evaluated by electrocochleography (Compound Action Potentials : CAP), and by observation of the anatomical alterations of the outer and inner hair cells (Scanning Electron Microscopy : SEM).

Pigmented guinea pigs are exposed to one-third octave band noise centered on 8 kHz at 129 dB SPL during 20 minutes. Continuous noise is used despite the fact that impulse noises represent the biggest hazard in the military environment because interindividual variability is smaller following exposure to continuous noise (up to now, in that study only a few animals have been exposed to impulse noises). Post-exposure audiograms (from 2 to 32 kHz) are performed 20 minutes and 1,2,3,7 and 14 days later and compared to the pre-exposure audiogram. After the last audiogram, the cochleas are prepared for SEM. The organ of Corti is thoroughly analyzed with respect to damage to inner and outer hair cells. Stereocilia pathology is defined according to Borg [37] : destroyed (a total loss of the stereocilia bundle), damaged (more than 10% disarray, fallen or lost stereocilia). Data are plotted as cochleograms representing the percentage of intact, damaged and destroyed hair cells every 200 microns from 2 to 10 mm from the base (first and then a half turn).

For each group of animals ($n = 10$), the treatment begins 1 hour after the end of the sound exposure and lasts for 5 days.

Carbogen therapy : carbogen mixture (7% carbon dioxide and 93% oxygen) is delivered at ambient

Hyperbaric oxygen therapy : animals are placed inside a pressure chamber. The chamber is pressurized at 2.5 ATA with 100% oxygen. The pressure is then held for 1 hour, twice a day. Decompression lasts 10 minutes.
Corticoid therapy : methylprednisolone hemisuccinate 2, 20, 40 or 100 mg/kg is given once a day by IM injection.
Combined hyperbaric oxygen – corticoid therapy : animals receive corticoids (20 mg/kg) and breathe hyperbaric oxygen (2.5 ATA).

4. Results

Figure 1 represents the results obtained in control (untreated) animals (n = 10). On the fourteenth day, the largest threshold elevation (about 20 dB) is observed between 8 and 13.4 kHz.

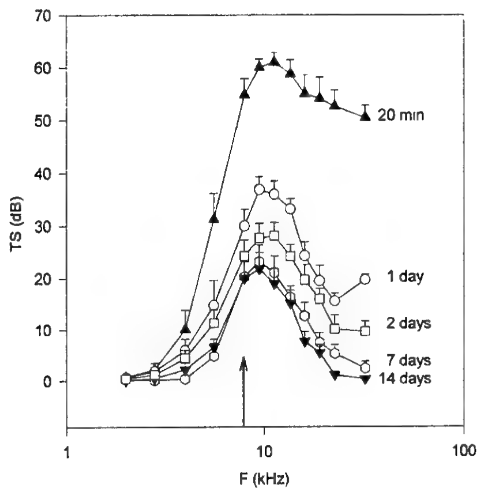

Figure 1 : CAP threshold shifts in dB
(mean value + 1 standard deviation)
(arrow shows exposure frequency)

To compare the threshold shifts (TS) and the cochlear damage, the audiograms and the cochleograms are scaled to adjust the distance from the base of the cochlea to the frequency. Three individual examples are given. The first example (figure 2) shows significant TS and cochlear damage (particularly in the first row of outer hair cells. The second example (figure 3) shows no TS (complete recovery) and no morphological damage. The third example (figure 4) shows that despite complete TS recovery, significant morphological damage can be observed. This indicates that CAP audiograms are not enough to fully assess a complete recovery (functional and morphological). Therefore, in man, an apparently complete functional recovery, as assessed by behavioral audiometry, does not exclude the possibility of (limited) hair cell damage. Such damage could make subjects more sensitive in case of further noise exposures and more susceptible to presbyacousis. Therefore, complementary functional tests (i.e., distortion product recordings which address directly the OHC) are advised.

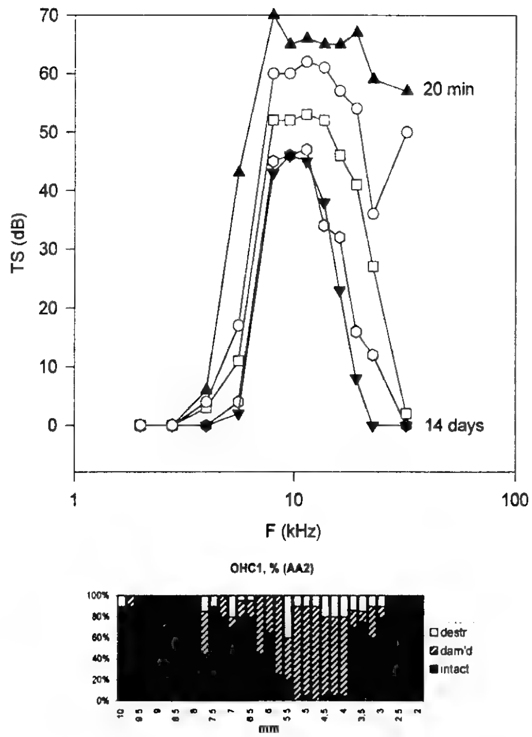

Figure 2 : TS and damage to the first row of OHC in a control animal

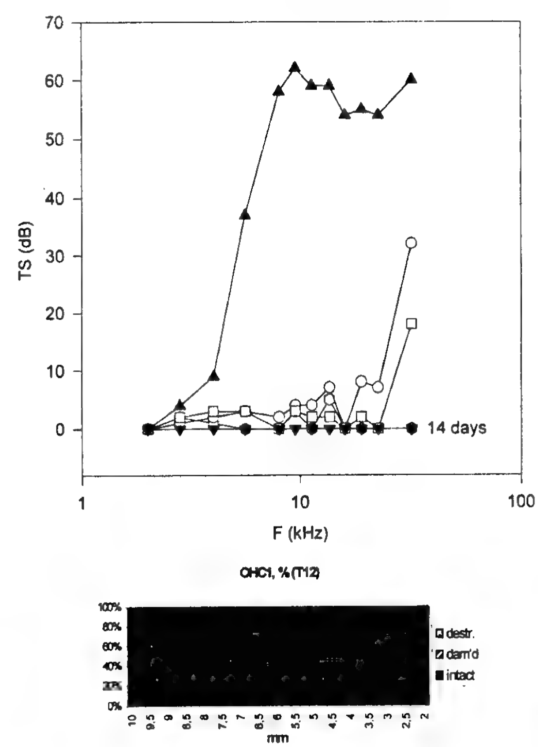

Figure 3 : TS and damage to the first row of OHC in a control animal

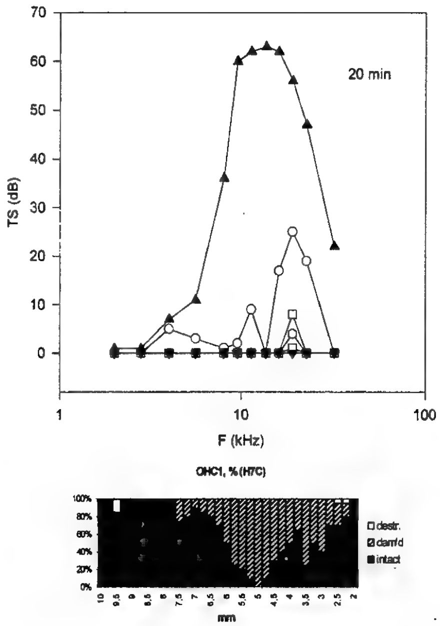

Figure 4 : TS and damage to the first row of OHC in a control animal

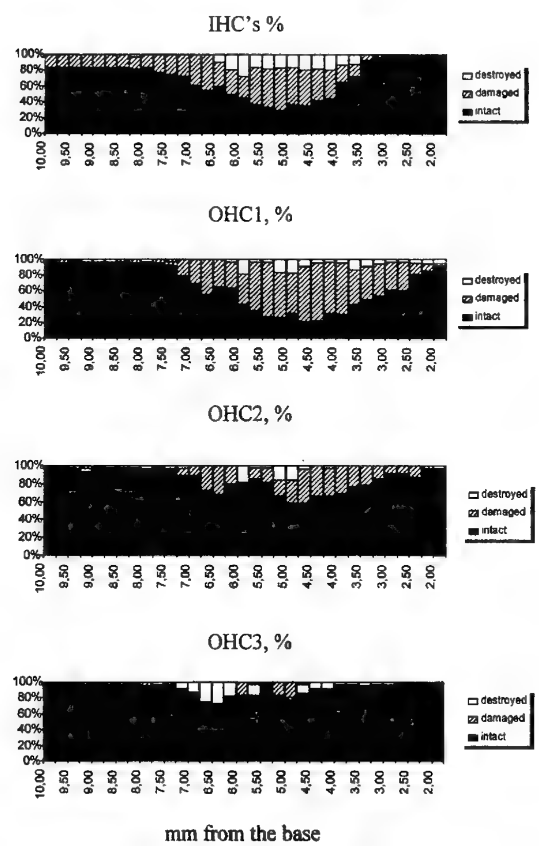

Figure 5 : Cochlear damage observed 14 days after acoustic trauma in controls (mean of 10 animals)

Figure 5 shows the cochlear damage observed 14 days after the acoustic trauma in control animals. The stereocilia of the first OHC row are the most sensitive.

Carbogen therapy : no significant difference for audiograms can be observed between the controls and carbogen-treated animals 14 days after acoustic trauma (figure 6). The cochlear damage (mean cochleogram) is not significantly different of that observed in controls (figure 5).

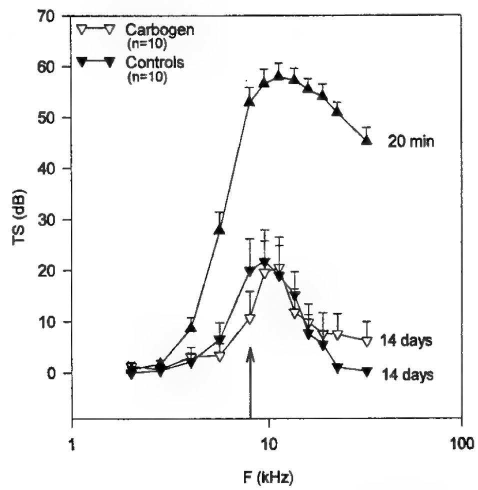

Figure 6 : TS in dB (mean + 1 standard deviation) observed 14 days after the acoustic trauma in controls and carbogen-treated animals

Oxygen therapy (ambient pressure) : as for the carbogen therapy, no significant difference is observed between controls and treated animals 14 days after acoustic trauma either for audiograms or for cochleograms.

Hyperbaric oxygen therapy : TS at day 14 are higher (40 dB instead of 20 dB) (figure 7) and cochlear damage is greater than in the control group (figure 8).

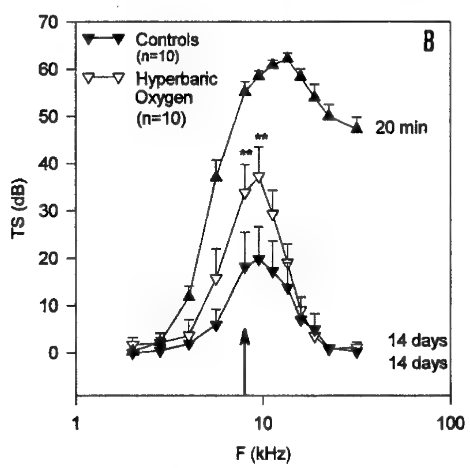

Figure 7 : TS observed at day 14 in controls and hyperbaric oxygen treated animals (** : $0.001<p<0.01$)

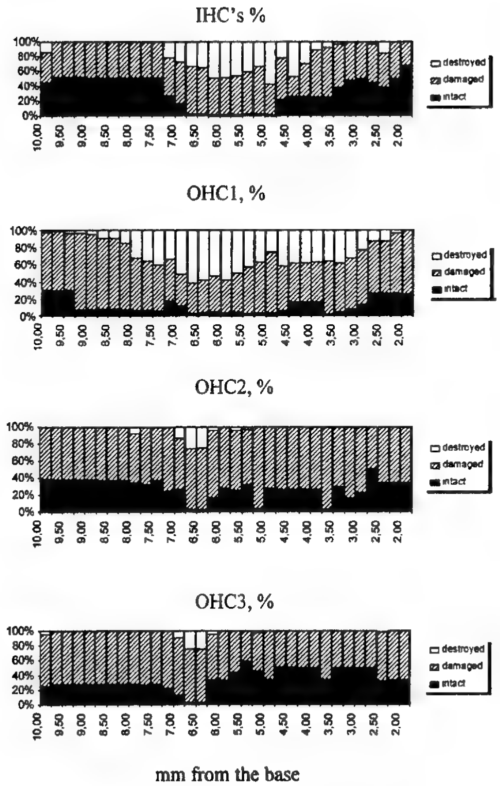

Figure 8 : Cochlear damage observed 14 days after acoustic trauma in hyperbaric oxygen treated animals (mean of 5 animals)

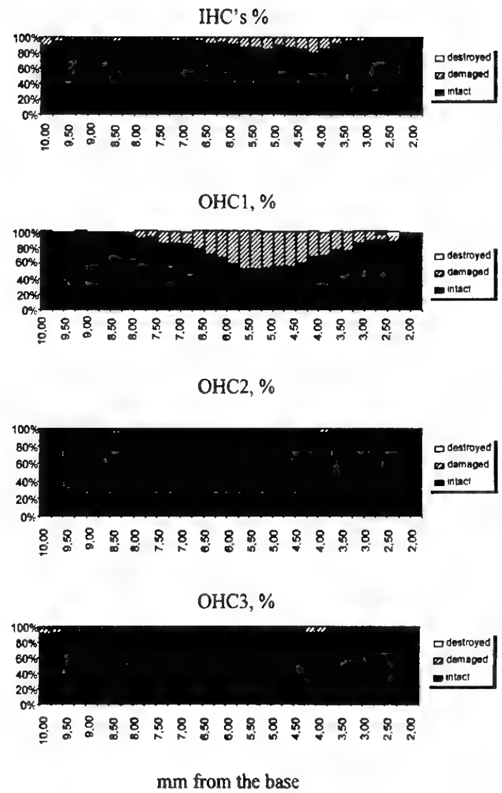

Figure 10 : Cochlear damage observed 14 days after acoustic trauma in corticoid treated animals (20 mg/kg) (mean of 10 animals)

Corticoid therapy : when the animals are treated once a day (for 5 days) with corticoid doses of 20 mg/kg, the TS recovery is faster and is improved : TS at day 14 are smaller (10 dB instead of 20 dB) (figure 9). Moreover, the cochlear damage observed on the fourteenth day in the treated animals is much smaller than in the controls and is almost restricted to the first OHC row (figure 10).

Dose-Dependent effect of corticoid : similar results are obtained when the corticoid dose is 10 mg/kg (doses larger than 20 mg show no further improvement either of the TS recovery or of the cochlear damage, doses smaller than 10 mg look ineffective).

Influence of the delay of the corticoid treatment : usually, the soldiers suffering acute acoustic trauma cannot be treated as early as one hour after the exposure.

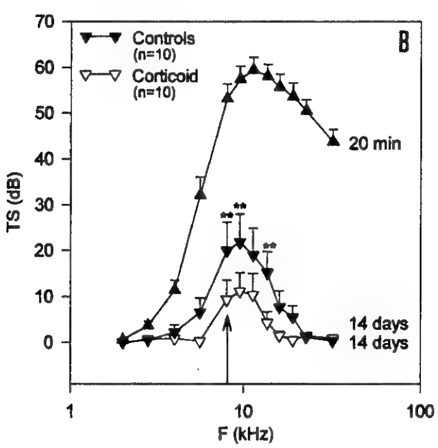

Figure 9 : TS observed at day 14 in controls and corticoid treated animals (20 mg/kg) (**: 0.001<p<0.01)

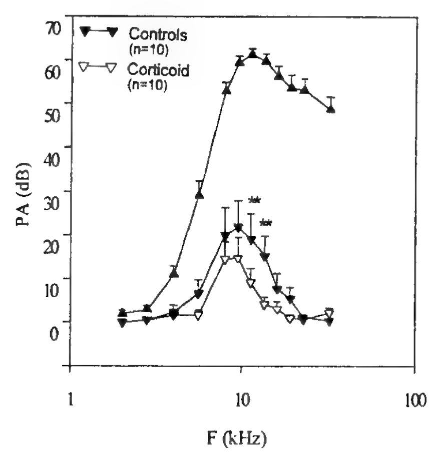

Figure 11 : TS observed at day 14 in controls and corticoid treated animals (20 mg/kg, first injection : 24 hours post exposure)

Therefore, another group of animals (n = 10) received the first injection of corticoids (20 mg/kg) 24 hours after the acoustic trauma (instead of 1 hour). The results which have been obtained are very similar to the previous experiment (figures 11 and 12).

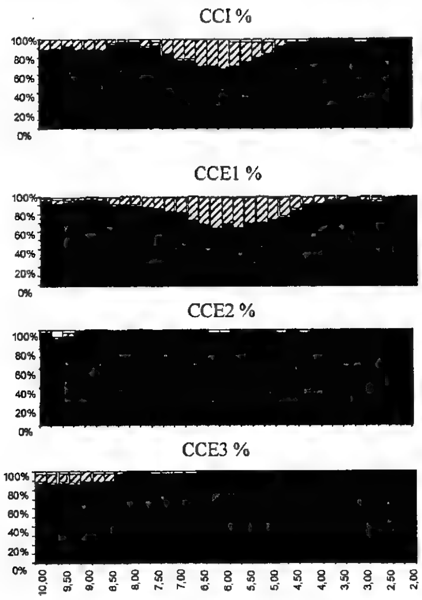

Figure 12 : Cochlear damage observed 14 days after acoustic trauma in corticoid treated animals (20 mg/kg, first injection : 24 hours post exposure) (mean of 10 animals)

The corticoid therapy is effective even when the delay of the treatment is 24 hours post exposure.

Combined hyperbaric oxygen – corticoid therapy : combining these therapies significantly improved the functional and morphological recovery (figure 13).

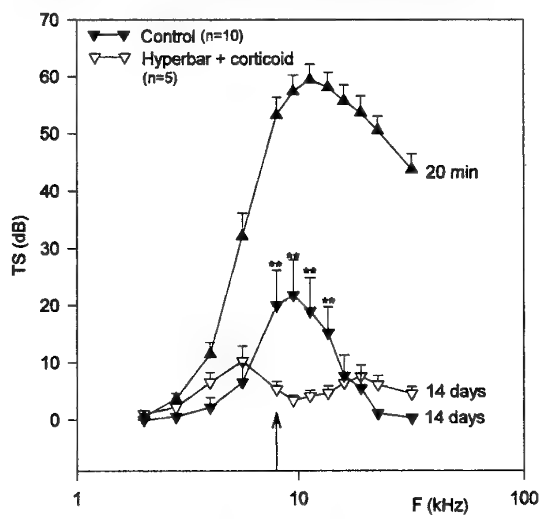

Figure 13 : TS observed at day 14 in controls and combined corticoid (20 mg/kg, first injection : 1 hour post exposure) - hyperbaric oxygen treated animals (n = 5) (**: 0.001<p<0.01)

These results are confirmed by a study of Lamm and Arnold [38] who observed that the combination therapy of hyperbaric oxygen and prednisolone achieved the best results of all treatments tested during acute experiments (3 hours post-exposure) performed on guinea pigs.

Corticoid therapy combined with hyperbaric oxygen therapy seems to help the hair cells to recover after an acute acoustic trauma. Without treatment, the hair cell damage remains stable or worsens between the immediate post-exposure period and day 14 (figures 13 and 14).

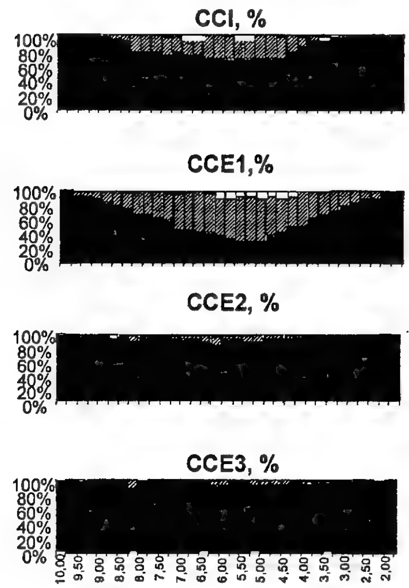

Figure 13 : Cochlear damage observed 1 hour after acoustic trauma in control animals (n = 10)

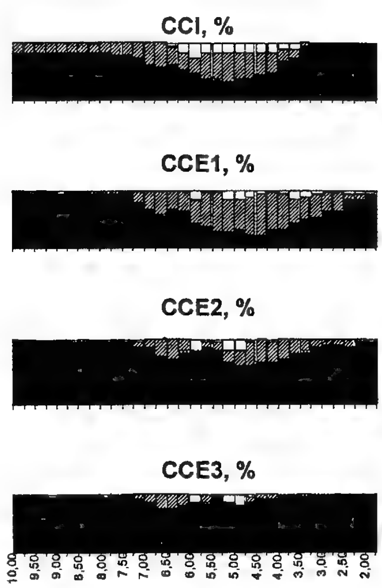

Figure 14 : Cochlear damage observed 14 days after acoustic trauma in control animals (n = 10)

Acoustic trauma from impulse noise

Acute acoustic trauma occurring in the military are mostly due to impulse noise. For impulse noise, it is very likely that the mechanical damage is the first and the main reason for NIHL. Therefore, it is also necessary to study the efficiency of the medical treatments following impulse noise exposures.

Guinea pigs have been exposed to impulse noises produced by primers. Number of rounds was 20 or 30 with 5 seconds intervals. The peak pressure level at the pinna ranged from 1 to 2.5 KPa corresponding to 154 to 162 dB peak (duration of the first positive phase: 0.12 ms). A control group was compared to a treated group with intra-muscular injection of methylprednisolone at the rate of 20 mg/kg; 1 hour after the trauma and once a day during 6 days after exposure.

The first results confirm the very large interindividual variability of the NIHL due to impulse noise and the "critical level" concept [38,39]. Control animals were exposed to 20 rounds of 2KPa peak pressure. Some animals present a very good recovery and almost no cochlear damage, some others present large TS at 14 days and complete destruction of OHC and IHC. Treated animals seem to recover better [40]. However, many more animals are still to be exposed and treated to know whether the treatment is efficient or not.

5. Discussion

Blood Flow Promoting Therapy

According to Lamm and Arnold [41], the cochlear hypoxia occurs simultaneously with hearing loss after exposure to impulse noise, gun shots, and broadband noise. Conventional approach to treating tissue ischemia and hypoxia is the administration of blood-flow-promoting drugs which affect vascular diameter, vascular permeability, membrane flexibility of red blood cells, blood osmolarity, plasma volume, and plasma viscosity, thereby improving microcirculation and tissue oxygenation.

One of these agents is the hydrophilic osmotic compound hydroxyethyl starch (HES), which is known to increase plasma volume, thereby decreasing plasma viscosity. As observed by Lamm and Arnold, in the noise-damaged ischemic cochlea the blood-flow-promoting effect is more pronounced and lasts longer after infusion of the high molecular HES 200 (compared to the low molecular HES 70). Since hemodilution due to the increase in plasma volume is more pronounced during HES 200, polarographic registration of PO2 does not improve. In contrast the less hemodilutive effect of the low molecular plasma expander induces a significant improvement of PO2, although full compensation of noise-induced cochlear hypoxia is not achieved. As compensation of noise-induced cochlear ischemia, the improvement of PL-PO2 ceases after termination of the infusion due to the relatively short plasma expansive effect of HES 70. However, both drugs show similar effects on auditory evoked potentials. Cochlear microphonic potential (CM) is partially restored and compound action potential (CAP) and auditory brain stem response (ABR) fully recover. It is assumed, that the osmotic effect of these hydrophilic compounds may contribute to restoration of disturbed cellular osmolarity and thereby cellular function. This hypothesis is supported by the observation that the vasodilator pentoxifylline (which has no such osmotic effect), fully compensated noise-induced cochlear ischemia and hypoxia, but had no therapeutic effect on NIHL (Lamm and Arnold) [41]. Simultaneous infusion of pentoxifylline and HES 70 or HES 200 does not attain better results than the monotherapy with HES 70 or HES 200.

Ginkgo biloba and naftidrofuryl are supposed to improve microcirculation, and thereby tissue oxygenation due to various effects not clarified so far. In the noise-damaged cochlea, however, blood flow and PO2 are temporarily improved during ginkgo infusion, but do not change with naftidrofuryl. As observed after infusion of isotonic saline (placebo), noise-induced reduction of CM, CAP, and ABR amplitudes do not differ from the untreated group, indicating that ginkgo biloba and naftidrofuryl had no therapeutic effect.

Carbogen is considered one of the most powerful vasodilators of cerebral capillary beds, and many studies indicate that carbogen inhalation during exposure to noise results in a significant reduction in noise-induced hearing losses [42]. Brown et al. [43] also found significantly less outer hair cell loss in guinea pigs given carbogen during a 120-dB broad-band noise exposure compared to a control group. It is assumed that the C02, in carbogen acts synergistically with oxygen in carbogen to produce increased oxygenation of cochlear tissues and to reduce cochlear damage. However, as previously reported by Hatch et al. [44], d'Aldin et al. [36] observed no significant difference between the carbogen-treated animals after the noise exposure and the control group. Therefore, carbogen could have a protective effect, but with much less curative efficiency.

Isobaric Oxygen Therapy

The idea that inhalation of pure oxygen could be used as a medical treatment for acoustic trauma is based on experimental studies which have shown that high-intensity noise causes cochlear hypoxia, which correlates with post-exposure hearing loss (Lamm and Arnold) [45]. These authors reported that cochlear hypoxia reflects an increased extraction rate from cochlear fluids. In another study, however, they showed that noise-induced cochlear hypoxia is not compensated by oxygen delivered at an ambient pressure level [46]. Improvement in threshold shifts is reported only when pure oxygen is given during noise exposure [44]. Accordingly, the effectiveness of oxygen delivered at the ambient pressure level after intense noise exposure is not shown in the study of d'Aldin et al. [36].

Hyperbaric Oxygen Therapy

The aim of hyperbaric oxygen (HBO) administration is to significantly improve partial oxygen pressure in

inhaled air. Oxygen is diffused from the various terminal cochlear capillary networks into the perilymph and cortilymph, supplying the sensory and peripheral neuronal structures of the inner ear, since these are not directly vascularly supplied. These diffusion paths are extremely long com-pared with noncochlear tissues. In this respect, the PO2 in the perilymph and cortilymph will only show a constant rise after an extreme increase in the arterial PO2 and thereby of the arterial-perilymphatic difference in oxygen concentration. This can only be achieved with HBO (with isobaric oxygenation, this difference in oxygen concentration is not high enough to show a clear and constant increase in intracochlear). The oxygen-induced reduction in cochlear blood flow in the noise-exposed ischemic cochlea is more pronounced after hyperbaric oxygenation compared to isobaric oxygenation. However, sixty minutes after termination of HBO, the cochlear blood flow is not significantly worse than in the untreated group Sustained compensation of noise-induced cochlear hypoxia is achieved most effectively by HBO. However, Lamm and Arnold [41] observed that an improvement in cochlear blood flow is not necessarily associated with improvement of auditory function..

At 2 ATA hyperbaric oxygen, the amount of oxygen and blood-dissolved oxygen fraction available are multiplied by 10. In the study of d'Aldin et al. [36], no improvement in threshold shifts can be observed, however, under those hyperbaric conditions. On the contrary, either at 2.5 or 1.5 ATA, hyperbaric oxygen treatment results in a higher threshold shift and additional hair cell damage.

Thus, oxygen administration is not decisive for medical treatment of acoustic trauma. Moreover, the higher threshold shift and additional hair cell damage observed in the d'Aldin's study, together with the fact that this treatment induces barotrauma in up to 50% of the human patients, suggest that hyperbaric oxygen should not be used –alone - as an acute treatment.

Antiphlogistic Therapy

According to Lamm and Arnold [41], the rationale for administration of anti-inflammatory agents in noise-induced cochlear alterations is based on the observation that inflammatory tissue alterations are not only elicited by bacterial, viral, or other immunopathological processes, but also by physically induced cellular damage, tissue hypoxia, and tissue ischemia [47].

In non-cochlear mechanically induced and/or hypoxic tissue an abnormal histamine liberation and/or release of eicosanoids such as prostaglandine, prostacyclin, thromboxanes, and leucotriens has been observed [47]. This results in various vascular effects, such as local arteriolar and capillary dilation and/or constriction and increased vascular permeability, all of which were also observed in sections of noise-damaged cochlear tissue. In this respect, an abnormal liberation of histamine and/or eicosanoids may be involved in the development of progressive cochlear ischemia beginning 30 min after termination of noise. It is assumed therefore, that anti-inflammatory drugs such as histamine H1-receptor antagonist, diclofenac sodium, and the synthetic glucocorticoid prednisolone (which counteract abnormal histamine liberation and/or release of eicosanoids), can relieve posttraumatic cochlear ischemia and the progression of noise-induced cochlear hypoxia. However, this is not the case at all.

In a recent study, Lamm and Arnold showed that prednisolone induces a significant decay in partial oxygen pressure in the perilymph as well in animals unexposed as in animals exposed to noise. These results indicate that corticoid induces oxygen consumption. In the short term (up to 3 hours post-exposure) study of Lamm and Arnold [41], there were no significant differences in the values for cochlear blood flow between the noise-exposed untreated group, the placebo-treated group and the groups treated with histamine N1-receptor antagonists diclofenac sodium, and prednisolone, administered either at a low or high dose. However, even though none of the applied drugs relieved progressive noise-induced cochlear hypoxia and post-traumatic ischemia, it is interesting to note that diclofenac induced partial restoration of CM and CAP amplitudes and full restoration of ABR. Following a high dose of prednisolone, there was again only a partial recovery of CM, but full restoration of CAP and ABR. A low prednisolone dose affected CAP only, while the histamine H1-receptor antagonist and isotonic saline had no therapeutic effect [41].

These findings indicate direct cellular effects of diclofenac and prednisolone in the cochlea. However, the precise mechanisms involved is mere speculation. Some of the cellular effects may contribute to related intracochlear early recovery processes associated with restoration of auditory function. In addition, prednisolone binds with equal affinity to both glucocorticoid and mineralo-corticoid receptors, the latter of which is very evident in peripheral auditory nerves and spiral ganglion cells. Binding by mineralocorticoid receptors results (among other effects) in an activation of the enzyme sodium-potassium-ATPase, which may contribute to restoration of disturbed cellular osmolarity, electro-chemical gradients, and neuronal conduction. At this point we have to remind that d'Aldin et al. [34] and Puel et al. [35] demonstrated that dendritic damage at the base of inner hair cells, the latter representing the site of CAP generation, accounts for half the contribution to acute hearing loss after acoustic trauma (especially in case of continuous noise exposure).

In the long term study of d'Aldin et al. [36], when the first injection of corticoid is given 1 h or 24 hours after exposure to noise, noise-induced threshold shift is decreased, recovery is faster, and less hair cell damage is observed (noise-induced hearing loss observed one day after corticoid administration: 25 dB, is almost equivalent to that observed 14 days after exposure in untreated animals: 20 dB). Thus, it seems that corticoid acts both at the dendritic and the cellular level. D'Aldin

et al. agree with the hypothesis of Lamm and Arnold: the activation of the enzyme Na, K-ATPase by corticoid may contribute to the restoration of disturbed cellular osmolarity, electrochemical gradients, and neuronal conduction. (indeed this enzyme is widely distributed in the cochlea, including the base of the outer and inner hair cells).

Even though the exact mechanism by which corticoids influence the inner ear function in those studies remains speculative, corticoid should be prescribed in treatment of acoustic trauma.

Combined Hyperbaric Oxygen-Corticoid Therapy

Corticoids induce oxygen consumption in order to mobilize amino acid for glucogenesis and to alter glucose utilization by oxygen-consuming mechanisms [48]. This oxygen consumption could explain the decline of partial oxygen pressure in the perilymph, observed in animals exposed to sound and treated by corticoids by Lamm and Arnold [47]. Moreover, acoustic overstimulation induces cochlear hypoxia which occurs simultaneously with hearing loss (this hypoxia reflects an increased oxygen consumption and hence increased extraction from cochlear fluids).

Thus, it looks interesting to combine corticoid and hyperbaric oxygen treatment. Improving partial oxygen pressure in inhaled air could compensate for the decline in partial oxygen pressure and thus potentiate corticoid effect. In agreement with this hypothesis, the results of d'Aldin et al. [36] indicate that combined corticoid and hyperbaric therapies significantly improve functional and, in a very striking way, morphological recovery. These results are in accord with those reported by Lamm et al., [41,47] in which hyperbaric oxygen combined with prednisolone gave best results.

These findings indicate first that effective treatment modalities of acute noise-induced hearing loss are available, and second that the therapeutic effects are not directly associated with blood-flow promotion and re-oxygenation, but involve other effects on the cellular level.

6. Perspective

A lot remains to be done to investigate the interest of other drugs (magnesium [49]...), the influence of the delay of implementation of the treatments and, most of all, to assess the actual efficiency of the treatments of the acute acoustic trauma following the exposure to impulse noise.

Moreover, experiments are in progress:

- to assess the interest of local treatments (i.e., the medicaments are applied directly to the inner ear [50]) which could be used together with the systemic treatments (i.e., the medicaments are given by perfusion to the whole body), or alone,
- to evaluate the interest of new treatments [51,52,53] which take advantage of the last advances in molecular biology (anti-oxydants, neurotransmitters agonists or antagonists, growth factors...) and could, besides cell preservation [54] and NIHL better recovery, lead to a decrease of the annoyance due to noise exposure related effects like tinnitus.

The increasing knowledge of molecular mechanisms, together with the development of new experimental approaches, is very promising for future clinical applications. Future progress will require that a method be developed and validated for the local application of drugs directly into the cochlea of human subjects.

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Cost Effectiveness of Hearing Conservation Programs

Doug Ohlin, Ph.D.
Program Manager
Hearing Conservation
U.S. Army Center for Health Promotion and Preventive Medicine
Aberdeen Proving Ground, MD 21010-5403, USA

In 1999, The Department of Veterans Affairs (VA) reported $291,622,148 for 56,792 veterans receiving hearing loss as a major disability. Civilian hearing loss compensation in that year was $35,346,392 for 6,406 Federal employees. The medical community has often qualified such data, noting that these monetary outlays do not reflect the more important factors of decreased job performance and loss in the quality of life. The reality of decreasing workforces and decreasing budgets have forced us, though, to market hearing conservation programs on the basis of economic benefits. Medical outcomes, spanning 20-years of rigorous program implementation, have been translated into over $500 million of projected training cost savings. Comparisons among the services have also been used to demonstrate cost avoidance for civilian hearing loss and VA disability. Explanations for differences among the services are presented. For example, the National Institute for Occupational Safety and Health (NIOSH) has made what they are calling a paradigm shift in their program focus from the agent (noise hazard) to preventing hearing loss. The Army Occupational Health and Industrial Hygiene leadership made this shift over 29 years ago.

The opinions expressed in this presentation are the professional opinions of the author. He does not represent the official position of the U.S. Army Center for Health Promotion and Preventive Medicine, the U.S. Army Medical Command, the Department of the Army or the Department of Defense.

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Hazardous noise pervades our military and industrial environments. The increasing demand for weapon systems with greater speed, range and firepower confounds the problem with higher and more hazardous noise levels. A soldier's ability to hear can be assaulted and damaged even before the completion of basic training. Prevention of noise-induced hearing loss in the U.S. Army is predicated on the fact that most hazardous noise exposure over a soldier's career occurs during such training exercises, not combat.

Readiness Benefits

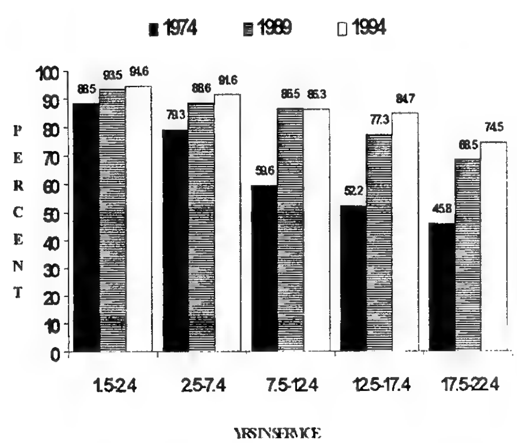
On today's high-technology battlefield, good hearing is an essential attribute of an effective soldier. Preserving a soldier's ability to hear low-intensity sounds or speech is critical to readiness and soldier survivability. Veterans of conflict value hearing as a 360 degree warning sense.

Monetary Benefits

In addition to a crucial role in soldier readiness and soldier survivability, there are also monetary benefits to be derived from effective hearing conservation programs. Commanders are saving more than nerve cells of the inner ear when they enforce the use of hearing protectors and ensure that troops report for scheduled health education briefings and hearing evaluations. Substantial reductions in hearing loss among U.S. Army combat arms personnel can be translated into reduced training costs and reduced hearing loss disability.

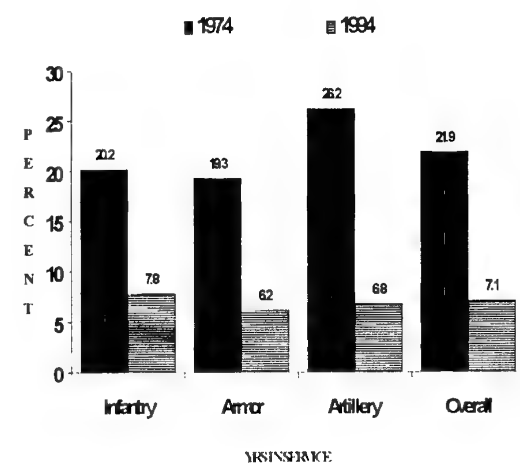
In 1974, Walden et al conducted a landmark study designed to determine the prevalence of hearing loss within U.S. Army infantry, armor and artillery enlisted branches that were at high risk for noise exposure.[1] Within each branch, soldiers were divided into five time-in service categories (see Figure 1).

Figure 1. Prevalence of Acceptable Hearing Among Armor, Artillery and Infantry Enlisted Personnel



On two occasions since, the Walden study was revisited.[2,3] In 1989 and 1994, soldiers were evaluated through an Army-wide, automated surveillance system [Hearing Evaluation Audiometric Reporting System (HEARS)]. The most significant findings were a 19 and 24 percent increase respectively in H-1 profiles (indicators of acceptable hearing).[4] This trend was consistent across all time-in-service categories in both studies indicating fewer soldiers with impaired hearing. Accordingly, there were corresponding reductions in H-2 and H-3 or greater hearing profiles (See Figure 2).[5,6]

Figure 2. Prevalence of H-3 or Greater Hearing Profiles in Enlisted Combat Arms



A hearing loss profile of H-3 or greater could be sufficient cause to remove a soldier from a Military Occupational Specialty (MOS) or an Area of Concentration (AOC) involving routine exposure to hazardous noise. They could even be vulnerable to an early discharge from the service. Depending on their experience and rank, a significant investment in their training could be lost. On the other hand, hearing loss prevented could translate into training costs saved. Based on Fiscal Year (FY) 1996 dollars, average training costs were computed for the level of training our enlisted soldiers would attend in a career progression (Table 1).

Table 1. Average Training Costs per Soldier for Enlisted Combat Arms Personnel (Direct and Indirect Costs with Student Pay)*

BT (Basic Training)	AIT (Advanced Individual Training)	BNCOC (Basic Non-Commissioned Officer Course)	ANCOC (Advanced Non-Commissioned Officer Course)
$8,743	$26,656	$22,205	$18,647

*Source: HQ TRADOC, Deputy Chief of Staff for Resource Management, Resource Analysis Division

Since the range of costs between schools varied up to $40,000, the cost averages were weighted based on the

number of soldiers reported in a particular MOS at that training level.

Differences between 1974 and 1994 in the prevalence of hearing loss by rank with strength data in June 1995 (101,080) were then used to calculate "cases of hearing loss prevented" at three pay-grade ranges in Table 2.

Table 2. Projected Training Costs Saved from Reduced Hearing Loss in Enlisted Combat Arms Personnel

Pay Grade	Training Level	Cases of Hearing Loss Prevented	Savings
<E05 (53.2%)	AIT ($26,656)	1,559	$41,556,704
E05-07(43.4%)	AIT+BNCOC ($48,861)	8,554	$417,956,994
>E07 (3.4%)	AIT+BNCOC+ANCOC ($67,508)	708	$47,795,664
Totals		10,821	$507,309,362

Because of the possibility that a soldier could be retained in the Army in an MOS without hazardous noise exposure, basic training costs were not included in these cost savings estimates. Otherwise, training costs were added as a soldier progressed from AIT to BNCOC to ANCOC training levels.

The weakest assumption in the aforementioned estimates is that everyone's calculated hearing profile is the same as the assigned profile. The last time this was checked on a large scale (over 20 years ago), approximately 65 percent of enlisted combat arms were assigned their appropriate hearing profile. Although the proportion has improved with reduced hearing loss prevalence and automated testing and calculation procedures, it would be naive to assume that appropriate hearing profile assignment is 100 percent. By default, based on the prevalence of H-1 profile, it is at least 89 percent.

For the purposes of this discussion, the savings reported are assumed to have occurred over an unspecified time at a consistent rate. In 1989, however, a replication of the 1974 prevalence study found an 11.0 percent prevalence in H-3 or greater profiles versus the 7.1 percent found in 1994.[2] Prevalence rates, therefore, were not consistent over time. The difficulty of specifying a time frame for the reported savings is also confounded by different turnover rates among MOS's. Such turnover rates were not available for these calculations.

As considerable as the projected half billion dollar savings, there are also other training cost savings not reported here. For example, there are also costs saved for training replacements and for re-training the individual profiled out of a noise-hazardous MOS for another MOS. Moreover, if we assume that the Hearing Conservation Program has had a similar positive impact among other enlisted personnel in the more technical MOS's as well as among officers and warrant officers, there is the strong possibility that training costs are being saved among them as well. Finally, basic training costs could also be saved for those who may have been medically boarded for hearing loss.

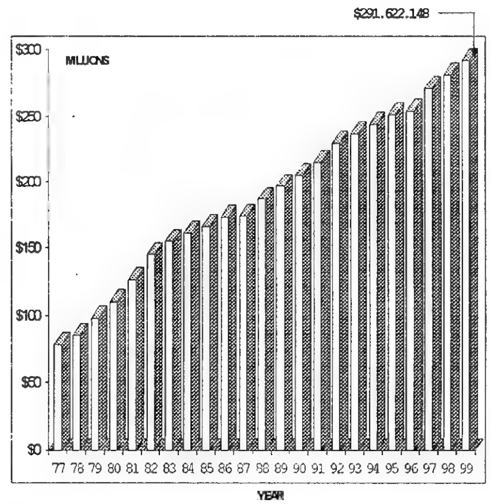
The reduced prevalence of H-3 hearing profiles reported above is consistent with a 15.1 percent decrease in major hearing loss disability cases for Army veterans since 1986. In this year, the Department of Veterans Affairs (VA) began to report hearing loss disability cases and cost by individual service. See Table 3 for the change in the percentage of cases since 1986 by service.

Table 3. Percentage of Change in the Number of Cases Reported from 1986 to 1999 for Major and Lesser Hearing Loss Disability by Service

	Major Cases	Lesser Cases
Army	-15.1	+38.6
Marines	+12.0	+77.1
Navy	-6.2	+109.1
Air Force	+21.0	+33.0

Monetary expenditures are reported by major disability, which is defined as the sole disability or the highest percentage disability in instances of multiple disabilities. See Figure 3 for total VA expenditures over the past 23 years.

Figure 3. Cost of Hearing Loss for All Veterans (Major Disability Only)
1977-1999 Total = $4,346,946,916



In 1999, the Army accounted for 61 percent (34,609) of the total major cases (56,792) and 54 percent (149,885) of all major and lesser cases (278,700). This accounting is roughly equivalent to the total Army numbers served since and including World War II, i.e., 60 percent of all service members.

In 1987, the VA changed their disability formula to include hearing test frequencies more affected by hazardous noise. Despite a liberalization of the disability formula, the data in Table 3 suggest a shift toward less severe hearing losses.

Comparisons among the services may not be appropriate in all cases. For example, the Air Force, created in 1947, does not have decreasing numbers of World War II veterans to affect their data. A comparison between the Marines and the Army is most tenable because of the similarity of our noise

exposures.

If the Army's percentage of change in the number of major cases had increased the same as the Marines (see Figure 4), the VA would be accounting for the additional Army major cases as shown in Table 4. When these "additional cases" are multiplied by the average costs of Army major disability cases, the estimated cost avoidance is notable, e.g., $333,159,418 from 1987-1999.

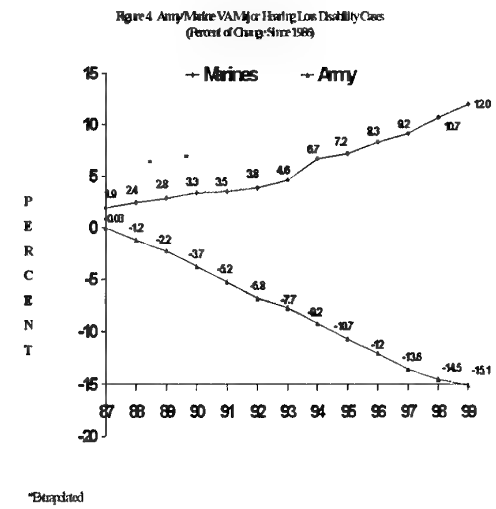


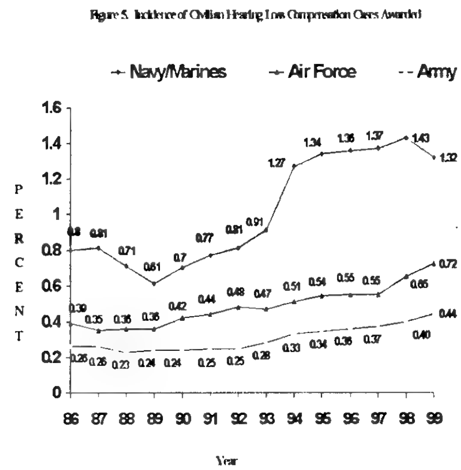
Table 4. Cost Avoidance Under Army vs Marine Percentage of Change in VA Major Hearing Loss Disability Cases

Yr	Additional Major Cases	X	Average Cost	=	Estimated Cost Avoidance
87	786		$2,923		$2,297,478
88	1,484		$3,157		$4,684,988
89	2,031		$3,343		$6,789,633
90	2,837		$3,518		$9,980,566
91	3,562		$3,724		$13,264,888
92	4,336		$4,026		$17,456,736
93	5,021		$4,179		$20,982,759
94	6,475		$4,338		$28,088,550
95	7,309		$4,528		$33,095,152
96	8,277		$4,606		$38,123,862
97	9,276		$4,965		$46,055,340
98	10,274		$5,174		$53,157,676
99	11,046		$5,365		$59,261,790

Total = $333,239,418

Total expenditures for civilian hearing loss compensation are considerably less than for VA disability. Moreover, the loss of a training investment is less of an issue with civilians. Such expenditures, however, are closer to home for installation commanders because of the charge back process. For example, the Department of Labor bills each government agency for the claims that the Office of Workers' Compensation Program (OWCP) have adjudicated. As each Army major command is billed for their share, installations are billed in turn.

Fortunately for Army installation commanders, the incidence of civilians awarded hearing loss compensation has been notably lower over the last 14 years than for the other services (Figure 5). For example, in FY 1997, the Army incidence of claims was almost two-thirds that of the Air Force and a quarter of those in the Navy. Direct hire populations (salaried and wage board) were used to compute incidence from 1986 to 1999.[7-20]



These favorable trends can also be translated into considerable cost avoidance. If the Army had the same incidence rates as the Navy, the OWCP would have had to account for 30,755 additional cases between 1986-1999. When the average costs in each year of Army civilian compensation cases are multiplied by the projected increase in cases under the Navy rate, the overall estimated cost avoidance for 14 years is $181 million.

Comparisons to the other services are considered valid under the following assumptions: (a) civilians enter employment among the services with comparable hearing levels; (b) the OWCP adjudicates hearing loss claims equitably among the services; and (c) tank and aircraft refurbishing operations are no less noise hazardous than shipyard operations.

Conclusions

The issue of differences between the services may not lie with the validity of the aforementioned assumptions, but rather with what the Army and Air Force hearing conservation programs do differently. It is no coincidence that the Audiology and Occupational Health elements of the Army and Air Force hearing conservation programs have traditionally focused on the exposed individual and the prevention of hearing loss rather than the noise hazard per se. Recently, the National Institute of Occupational Safety and Health (NIOSH) has made what they are calling a paradigm shift from a focus on the agent (noise hazard) to preventing hearing loss. The Army made this shift over 30 years ago.

Although elimination or reduction of the hazard is the most desirable option, it was not technically or economically feasible to engineer noise down to safe levels in tanks or 155 howitzers, etc. The industrial hygiene focus on measuring the noise and hoping for noise abatement was shifted to more pragmatic strategies for preventing hearing loss.

In the Army and Air Force, the use of hearing protection is enforced regardless of duration of exposure when noise hazardous thresholds are reached. In some cases, personnel are overprotected but more susceptible individuals are better protected and off-the-job noise exposures are more readily accounted for. Sufficient numbers of military audiologists have also facilitated an increased capability for monitoring audiometry and health education in the Army and Air Force. Until recently, the Army had more than three times as many military audiologists than the Navy and twice as many as the Air Force. In addition, the Army has had a mainframe data base of audiometric records for the last 15 years which was based on an existing Air Force model. Through these corporate data bases, the Army and Air Force have been able to report measures of program participation, quality assurance and program effectiveness. In addition, the Army successfully automated audiometric data collection from the field 12 years ago and the Air Force is following suit.

Neither adequate audiology staffing or the availability of these essential management tools would have been possible without enlightened leadership among senior Army and Air Force Occupational Health and Industrial Hygiene personnel. The bottom line for effective hearing conservation programs, however, is command support at all levels. The bottom line for value added, though, may not reside in cost benefit analyses of over one billion.
No matter how substantial, such monetary projections do not reflect the more important factors of decreased soldier readiness, decreased job performance and the loss in the quality of life associated with noise-induced hearing loss.

Doug Ohlin is the Program Manager of the U.S. Army Hearing Conservation Program at the U.S. Army Center for Health Promotion and Preventive Medicine. He is currently chairman of a DoD Hearing Conservation Working Group and President-Elect of the National Hearing Conservation Association. For the last 28 years he has provided technical and administrative assistance to the Office of The Surgeon General and the Army Medical Department.

Notes

1. Brian E. Walden, Richard A. Prosek and Donald W. Worthington, _The Prevalence of Hearing Loss Within Selected U.S. Army Branches_ (Washington, DC: U.S. Army Medical Research and Development Command, 1975) Interagency IOA 4745.
2. Doug Ohlin, Kenneth B. Aspinall and William H. Monk, "Hearing Conservation in the U.S. Army", _The Journal of the U.S. Army Medical Department_ (Fall, 1994) pp 38-42.
3. Doug Ohlin,"U.S. Army Hearing Conservation Program Yields Cost Avoidance from Reduced Veterans Hearing Loss Disability", _USACHPPM Today_, Vol 2, No. 2 (July 1995).
4. H-1 Army Hearing Profile. Audiometric average level in each ear not more than 25 dB at 500, 1000, and 2000 Hz, with no individual frequency greater than 30 dB. Not over 45 dB at 4000 Hz. Military hearing profiles are determined from audiometric test results of pure tone hearing thresholds.
5. Poor Hearing. Equivalent to the upper limit hearing thresholds of H-2 military hearing profile, e.g., audiometric average level not more than 30 dB at 500, 1000, and 2000 hertz (Hz) with no frequency greater than 35 decibels (dB) and no greater than 55 dB at 4000 Hz; or better ear must be better than 30 dB at 500 Hz, 25 dB at 1000 Hz, 25 dB at 2000 Hz and 35 dB at 4000 Hz.
6. H-3 or greater Army Hearing Profile. Greater hearing loss than an H-2.
7. _Defense 86_ (September/October) pg 35.
8. _Defense 87_ (September/October) pg 37.
9. _Defense 88_ (September/October) pg 35.
10. _Defense 89_ (September/October) pg 35.
11. _Defense 90_ (November/December) pg 35.
12. _Defense 91_ (September/October) pg 35.
13. _Defense 92_ (September/October) pg 35.
14. _Defense 93_ (Almanac) pg 35.
15. _Defense 94_ (Almanac) pg 35.
16. _Defense 95_ (Almanac) pg 25.
17. _Defense 96_ (Almanac) pg 25.
18. _Defense 97_ (Almanac) pg 25.
19. Department of Defense Website.
20. Department of Defense Website, http://web1.whs.osd.mil/mmid/civilian/sep99.htm.

Non-Auditory Damage Risk Assessment for Impulse Noise

Daniel L. Johnson
Brüel Bertrand Johnson Acoustics
4719 Mile High Drive
Provo, Utah 84604 USA

Abstract This paper discusses the non-injury thresholds established for three different complex waveforms. These animal studies were accomplished by EG&G at the Blast overpressure Test Site at Kirtland AFB in New Mexico. Human volunteer studies were also performed. The human studies verified non-injury levels for three different freefield waveforms and one complex waveform. The use of the Bowen model developed nearly 40 years earlier, as well as two later models, will be discussed. A simple relationship between an "acceptability limit" and the non-auditory injury limit was found to exist. This "acceptability limit" was found to be approximately 70 % to 80% of the non-injury limit in peak pressure in kPa. This small reduction in peak level provides a sufficient safety factor for all possible waveforms, both complex and freefield, and a simple mathematical equation is recommended as a practical design goal.

Introduction Criteria for non-auditory injury for freefield impulse noise has been available since the late 60's (Richman, et. al., 1966 and Bowen, et. al., 1968). Gas containing organs were found to be much more vulnerable to direct blast than solid organs. Using this knowledge, Bowen established criteria using an early model based on the response of the lungs to a simple Friedlander wave. Criteria for complex impulsive waveforms, however, have been virtually non-existent until recently. Over the last ten years there has been some significant changes. Two new computer based models have been proposed. (Axelssen and Yelverton, 1996 and Stuhmiller, et. al., 1996) In addition, animal experimentation has demonstrated the non-injury threshold levels for three different complex waveforms.(Yelverton, et al, 1993,Yelverton, et al, 1997, Yelverton, et al, 1997, Merickel, et al, 1997) A human study, using 60 subjects, has verified these limits for one of these three complex waveforms.(Johnson, 1998) Human studies have also verified a non-injury level for three different freefield exposure conditions consisting of both 6 and 100 exposures spaced at one-minute intervals.(Johnson, 1994 and Johnson 1998) Over 120 subjects were used for the waveform that was like a large howitzer. About sixty subjects were used for each of the waveforms that were more like mortar fire. These results serve as very strong anchor points for any non-auditory risk criteria. It would have been useful for human studies to have backed up the animal results for all three complex waveforms, but budget cuts prevented this from happening. However, the results of the animal studies have so far been a good predictor of the human results. This encouraging result suggests that some simple criteria using some "worst case waveforms" can be proposed for complex waveforms in general. These criteria will err on the safe side. In the cases that this is not acceptable, use of one of the computer models is suggested.

Freefield waveform criteria

The Bowen Model: Numerous mammalian mortality studies have demonstrated that tolerance to classical blast waves is dependent upon the peak overpressure, the overpressure positive phase duration and the animal species. (Richman, et al, 1968,Bowen, et al, 1968). Review of mortality data shows three concepts: 1. The data separates into "small" and "large' mammal groups; 2. There is a linear relationship between the probability of mortality and the logarithm of peak pressure and 3. The lines have a common slope, suggesting a common mechanism of lethality. For these reasons, it is not surprising that sheep should serve as a good model for determining the effects of blast on humans. Unfortunately, because being based on lethality data, the Bowen model is more accurate at the 50% lethality point than at the "threshold of injury point." However, the Bowen curves have been extended down to include threshold of injury. Thus the shape of the curve with respect to peak pressure versus duration remains the same. There is some early animal data that support the Bowen reflective threshold limit curve as shown in figure one, but the best support for the general shape of this curve comes from recent human data.

Recent Human Exposures Because the U.S. Army was concerned about non-auditory injury from training with large weapons, the Army began to use the Z-curve plotted in figure 1. . This curve was considered a conservative non-auditory limit as well as a limit for hearing conservation while wearing hearing protection. This Z-curve is based on auditory data from small arms fire and was developed by U.S. National Research Council Committee as criterion for preventing hearing loss from impulse noise. (CHABA, 1968). Because the Z-curve was considered likely to be very over-protective with respect to non-auditory risk, some studies designed to be at the expected non-auditory

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limits for several weapon systems were funded by the U. S. Army. These were started in 1989 and completed in 1997.

The results of the human studies are plotted in figure 1. The human studies come from the final reports of the blast overpressure studies recently finished at Kirtland AFB for the U. S. Army. (Johnson, 1993, Johnson, 1997) At the highest peak pressures, which occurred six times at I minute intervals, with but two exceptions, no non-auditory injury was observed. There were 104 subjects for the 190 dB, 3-ms duration exposures; 67 subjects for the 193 dB, 1.4-ms duration exposure; and 52 subjects for the 196 dB, 0.8-ms duration exposure. One of the two exceptions was a hematoma on the eardrum of one subject whose ear was only protected by a leaking muff. The other exception was a subject that had bruised his ribs by playing football. He complained that the blast caused great discomfort to his ribs and eventually he elected to drop from the study. These exposures all fall below the Bowen reflective limit curve of figure 1. The shape of the reflective limit curve, at least for these conditions, seems to be reasonable.

Complex waveform criteria The response of mammals to complex waveforms has been difficult to interpret. Peak pressure and duration of the positive pulse are not sufficient descriptors of the waveform. The rate of rise, the amount of the negative phase, the location of the maximum peak in time, and the frequency of oscillation may be additional parameters of importance. For example, the protective effects of "long-duration" pressure loading has been demonstrated by pressurizing animals to increasingly larger ambient pressure levels prior to blast exposure (Damon, et al, 1966). It was found that resistance to blast injury increased as the ambient pressure increased. To resolve some of the difficulty, animal experimentation undertaken to determine the non-injury limits for several types of typical complex waveforms.

Recent Animal Exposures The recent animal exposures have consisted of three different types of waveforms. The first wave form is of the type typical of shooting a recoilless rifle out of a bunker. As shown if figure 2, this waveform is characterized by a very long duration of highly oscillating pressure. The second waveform used is one characteristic of an enclosed space that is open to the pressure wave of a large muzzle blast. This could occur in a self-propelled howitzer with its doors open. As shown in figure 2, this waveform has a rather slow rise time as well as a long and significant negative pressure phase. The third waveform used is one characteristic of firing a mortar out of a partially enclosed space such as an armored personnel carrier. This waveform has a small precursor wave followed by a more classical freefield wave, then a significant negative wave.

1) Firing from bunker results. An early study in 1976 using rabbits suggested a significant risk of non-auditory injury from firing the Carl-Gustaf recoilless rifle. Using two or three shots at 1 minute intervals, nearly 35% of the rabbits sustained moderate to severe injuries from peak pressures not exceeding 186 dB (40kPa). The spectral analysis of the waveform showed the strongest pressure components to be in the 150-500 Hz range. This range matches the natural frequency of the rabbit, (von Gierke, 1968), thereby enhancing injury (Clemedson and Jonsson, 1976). At Kirtland AFB in the early 1990's, a 17.3 cubic meter chamber was built to serve as the bunker. Explosive charges were detonated outside of the bunker and some of the resulting blast was funneled into the bunker through a pipe 249 cm. in length and 20.3 cm in internal diameter. The typical resulting blast wave inside the chamber is shown in figure 2a. In a study using sheep that was completed in 1993, the proven sub-threshold of injury level was shown to be 48 kPa for one shot, 44 kPa for 3 shots. (Yelverton, et al, 1993) In 1997,19 sheep were used to verify a sub-threshold level of 23 kPa for 100 shots (Merickel, et al, 1997).

2) Self propelled howitzer muzzle blast results (Yelverton, et al, 1997): At the Army blast pressure test site, the hull of an M108 Self propelled howitzer with the back door open was used as the crew compartment. The muzzle blast was simulated exploding C-4 inside a large tube and directing the resulting blast waves over the M108 hull. A reflector was used to reflect some of the blast into the hull. See figure 2b for the resulting simulation. Sheep were exposed to the blasts at one-minute intervals. One subject was supported vertically in the gunner position and one subject was supported vertically in the loader position. Twenty-two controls were used during the study. Using 30 sheep, it was found that the sub-threshold of injury was 27 kPa for 6 blasts. Using 10 sheep for the 25 blast sequences and 40 sheep for the 100 blast sequences, it was found 20 kPa was the sub-threshold level for both sequences. Unacceptable number of lesions to the pharynx/larynx occurred when the overpressure was 32 kPa for 6 blasts (6 lesions out of 10 animals) and 24 kPa for 25 blasts (3/10).

3) 120mm mortar blasts from an enclosed space results (Yelverton, et al, 1997): At the Army Blast over pressure Test Site, a vertical explosively driven shock tube, in combination with reflector plates, was used to simulate the waveform of the 121mm mortar shot out of an Armored Personnel Carrier. The resulting waveform is shown in figure 2c. Using C-4 as the explosive charge, the blasts were set off in one-minute increments. The results of the study demonstrated sub-threshold injury level as 36 kPa for 6 shots each and as 30 kPa for 50 shots each.

Recent Human Exposures

Firing from the bunker results: After the sub-threshold levels were established by exposing anesthetized sheep, a walkup study at the Army Blast Overpressure Site

using 64 army volunteers was started in 1994 (Johnson, 1997). The same bunker simulation was used. Because of the need to start the exposures at very low levels so that the subjects could become acclimated to the blasts, the first level was at a peak of about 6 kPa. for one shot. The levels were increased in 7 steps to 48 kPa. If a subject passed that level, the next exposure was two shots at 44 kPa. The final exposure was 3 blasts at 44 kPa. Fifty-nine subjects passed through the entire exposure sequence without any known problem with respect to non-auditory problems. Three subjects elected to quit and two subjects were dropped for administrative reasons. Daily medical exams, including hemoguaiac testing, verified the lack of any injury. For these reasons, the sheep did serve as a conservative model for predicting safe, non-auditory exposures in humans.

The models There are two published approaches for modeling the human response to complex waveforms. These are a model proposed by Axelsson and Yelverton based upon maximum chest velocity (Axelsson and Yelverton, 1996) and a model proposed by The Walter Reed Army Institute of Research/ JAYCOR based on work (Stuhmiller *et. al.*, 1999).

Neither or these models are commercially available and have not been standardized. Until this occurs, neither one of these promising models will fill the needs of the design community.

1) The chest velocity model: Axelsson and Yelverton took a single degree of freedom model, originally developed to measure the response of the thorax to simple Friedlander waves, to calculate chest wall velocities resulting from complex waveforms such as shown in figure 2 (Axelsson and Yelverton, 1996). The results found with sheep demonstrated a good relationship between the overall Injury Index (which included the lungs, upper respiratory tract, gastrointestinal tract and solid intra-abdominal organs) and the calculated maximum inward chest velocity. They also found a good correlation between chest wall velocity and the established Friedlander prediction curves of the Bowen model. The velocity of complex blast waves was nearly the same as that of Friedlander wave for a given degree of injury. These velocities were found to be 3 to 4.5 meters/second for the threshold of injury, 8 to 12 meters/second for 1-% lethality, and 12 to 17 meters/second for 50% lethality. (Axelsson and Yelverton, 1996)

2) The Walter Reed Army Institute of Research/ JAYCOR BLAST INJURY model: (Stuhmiller *et. al.*, 1999) For more than ten years the U.S. Army has funded an effort by JAYCOR to develop a lung injury model. The mathematical model of the chest wall dynamics, and the resulting pressure waves in the lung, is used to predict injury. (Stuhmiller *et al.*, 1996) The model has been compared, and I assume adjusted, to the relative large number of animal data from the Army's Blast Over-pressure studies as well as other studies. One of the bases of the model is the observation that the incidence of injury follows a log normal correlation with the computed total energy in these waves. Thus this relative simple model allows lung injury be predicted from measured or predicted pressure traces. (Stuhmiller *et al.*, 1996) It is worthy to note that the sub-threshold of injury freefield overpressure levels that were used to establish the upper levels for 6 shot and 100 shot sequences for the human exposures came from an earlier version of this model. According to JAYCOR, the model is being evaluated by a third party review and has not been formally released. This is a step that must be done. Also, this model only predicts lung injury, using the assumption that lung injury is the precursor to any other type of injury.

Possible Criteria for both Complex waves and Friedlander waves In figure 3 the data from the various animal and human studies are plotted on a common graph. The Bowen threshold curve is also plotted. They are quite consistent with each other. In fact, I believe that a simplified model can be derived from the data plotted in this figure. One of the keys of doing this is the observation that the various complex waveforms serve as a set of worse case examples and that most complex waveform will be a less injurious subset of these waveforms given that the peak pressure is the same. This will be discussed further in the following paragraph. One of the factors that is not discussed is the acceptability of a human to expose himself or herself right at the threshold of injury. For many of the human volunteers, there was a definite reluctance to expose themselves at the very top level. The exposure ceased to "be fun". My belief that there will be a greater chance a weapon will be used properly if it is not scary to use. For this reason, the criteria will be reduced slightly. This reduction also builds in a slight safety margin in case are assumption that we have used worst case waveforms is not quite true.

Worse case waveforms Figure 2 shows three waveforms that were selected to be typical of different types of complex blast waves. What is not shown is the effort by the investigators, in this case John Yelverton and myself, to make these as dangerous as possible. For example, the bunker, in which the firing from the bunker simulation was made, was designed to resonant at the frequencies from 50 – 60 Hz. These are the natural frequencies of the chest and for that reason are expected to be the most dangerous. For the Self-propelled howitzer, a considerable effort was expended to produce the long negative pressure that followed the initial positive part of the wave. The idea was to make the lung expand more quickly after the initial compression. My contention is the most complex waveforms will be less dangerous that the ones used in figure 2. A perfect application of the mathematical models described above is to challenge this contention.

Human Acceptability At the end of a subject's exposure to a specific waveform at all the

different number and levels of blasts, the subject was given two sets of questionnaires related to acceptability. One set of questions simply asked if he would find it acceptable to train at the various exposures that he received. The other questionnaire asks the subject to mark one of the 5 statements the most closely related to his feelings (Johnson, 1993 and Johnson, 1997). The results of these questions for the three freefield waveforms and the firing from bunker waveform are summarized in table 1. The exposures that were at the threshold of the non-auditory limits were the 6 shot exposure at level 7 and the 100 shot exposure at level 6. There was approximately 3 dB difference between the levels. Note that the dislike of the subjects for the exposures increases quickly when level 7 is reached. Likewise, the dislike increases at level 6 as the number of blasts in increased. Should a weapon designer worry about acceptance? Clearly a certain percentage of the subjects did accept the exposures. In fact, there were a few subjects that were disappointed in that there were not higher exposure levels available, especially for the 6 blast sequence. I know that I would have been exposed to a higher level in the firing from the bunker simulation. Having been exposed to several shots at all the waveforms, I felt that the bunker simulation was the weakest of the lot with respect to physical discomfort. The subject generally stated that the number of exposures became a problem past 25 blasts per day. This can be seen in table 1. The subjects were given a count down so that they could be prepared when the blast occurred. Without this count down, the acceptance of these exposures would certainly be lower.

Table 1. Percent of the subjects that rated the stated exposure as unacceptable with respect to training. There is about a 3 decibel difference between levels.

	Level 7	Level 6	Level 5	Level 4
Bunker 1 shot	20*	12	3	1
1 meter 6 shot	40*	3	0	0
3 meter 6 shot	37*	0	0	0
5 meter 6 shot	36*	0	0	0
Bunker 3 shot		25*	8	1
1 meter 100 shot		69*	32	14
3 meter 100 shot		48*	33	10
5 meter 100 shot		57*	26	11

- ***Non-auditory sub-threshold of injury***

Recommended design criteria The design criteria that I recommend is as follows:

For free field waves with a clearly defined A-duration under 10 ms

Max peak = 195 dB – 10 log (A-Duration) –2.5 log (N)

And for all other transient waveforms

Max peak = 185 dB-2.5 log (N)

Where: The max peak is an average with a standard deviation of less than 1 dB

The A-duration is the time in millisceconds that the positive going peak overpressure stays positive without going negative.

For non-freefield waveforms, the Max peak is the greatest overpressure observed during the transient.

N is the number of individual transients during any day.

Comments; The proposed criteria should handle any conceivable waveform. In basically ignores the duration of a complex waveform as based on the fact that all of the animal research up to now has shown that the peak overpressure is a better measure of the non-injury level. Nevertheless, these levels are approximately 2 decibels lower than probably the true threshold to account for human acceptability and to provide a small safety factor in case the worst case assumption is not quite true. The long A-duration that in likely from a nuclear explosion is also covered by this criteria due to the fact that 185 dB is the approximated level that the non-injury curse of Bowen asymptotes with respect to duration.

Exceptions The suggested criteria do not handle the case where the blast causes an airflow such as when a blast enters a structure with a door. The resulting displacement of a body is outside the scope of these criteria.

Conclusions Considerable human and animal data now exists with respect to a non-injury threshold for both simple and complex waves. A simple criterion for the sub-threshold for blast injury has been proposed. One of the key concepts for this criterion is to eliminate the

concept of duration for complex waveforms. The levels have been dropped slightly to make the exposures more acceptable to the exposed soldiers and to provide a small safety factor. This approach provides a lower bound with respect to the non-auditory threshold for any complex waveform. In order to raise this limit for a complex waveform that might not be as injurious as the waveforms that established the criteria, the use of one of the existing models is suggested. These models are referenced; however, they are not as readily available as they need to be. They need to be standardized and provided as a software program, perhaps one that can be downloaded from a website.

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Figures

Figure 1 The threshold of lung injury from the Bowen model (Yelverton, et al, 1996) as well as the Z-curve used in MIL-STD-1474C. Also plotted are various data from humans, sheep and dogs. The open circles were cases in which no petechiae were observed. The half-filled circles indicate that one-half of the dogs or sheep had some petechiae on the lungs. The solid circles indicate that some small isolated hemorrhages occurred. For the human studies, the lack of lung petechiae is assumed from the lack of petechiae on the larynx-pharynx. The F and R indicate the exposure was freefield or reflective, respectively. Adapted from figure 9 of Yelverton, et al, 1996.

Figure 2

a Pressure time pattern from "Firing anti-tank weapon from the bunker" simulation

b Pressure time pattern from "Firing 155 Self Propelled Howitzer with open doors" simulation

c Pressure time pattern from "Firing 121 mm mortar from Armored Personal Carrier" simulation

Figure 3 The fit of the data to the proposed formula: 195 dB –10 log(T) – 2.5 log(N).

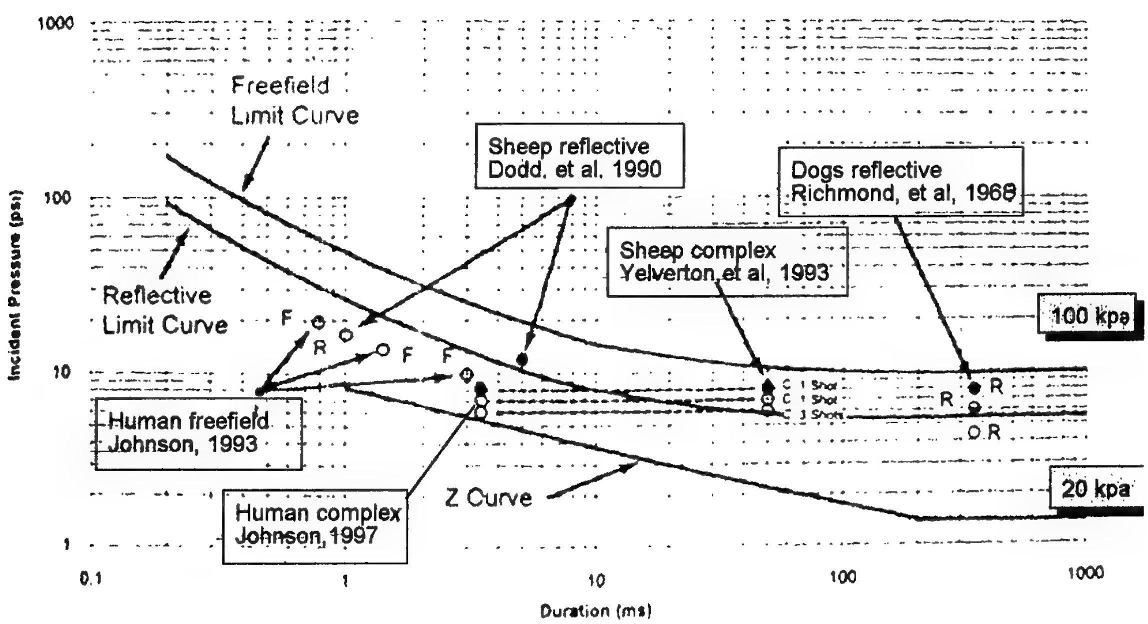

Figure 1

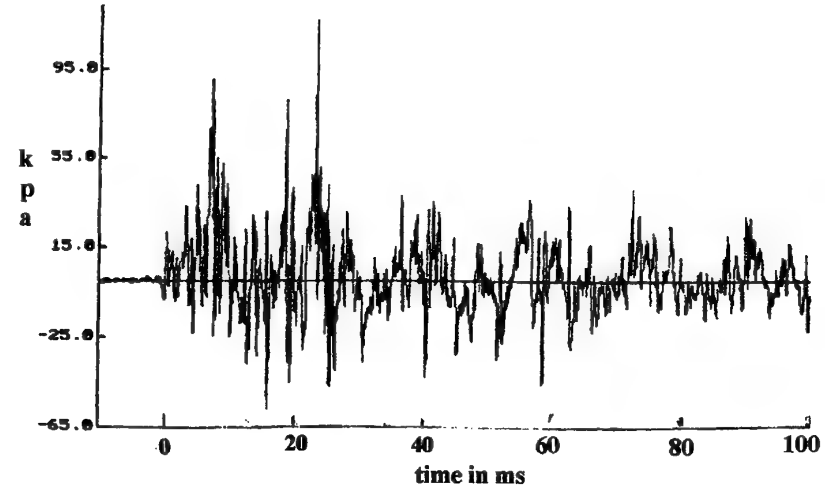

Figure 2a Pressure time pattern from "Firing anti-tank weapon from the bunker" simulation

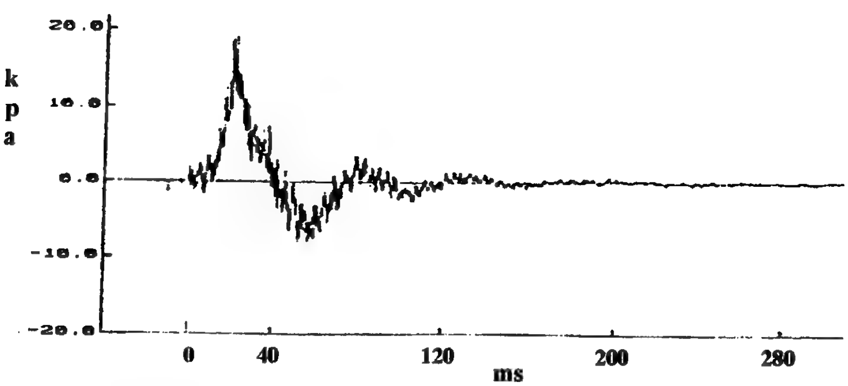

Figure 2b Pressure time pattern from "Firing 155 Self Propelled Howitzer with open doors" simulation

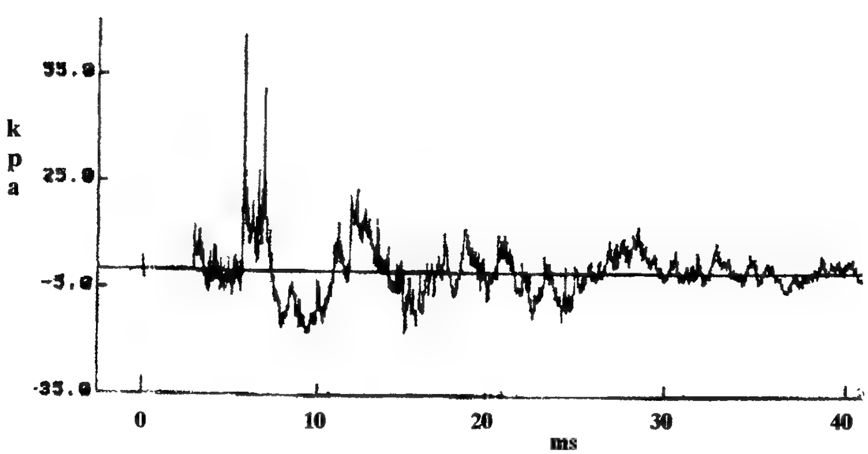

Figure 2c Pressure time pattern from "Firing 121 mm mortar from Armored Personal Carrier" simulation

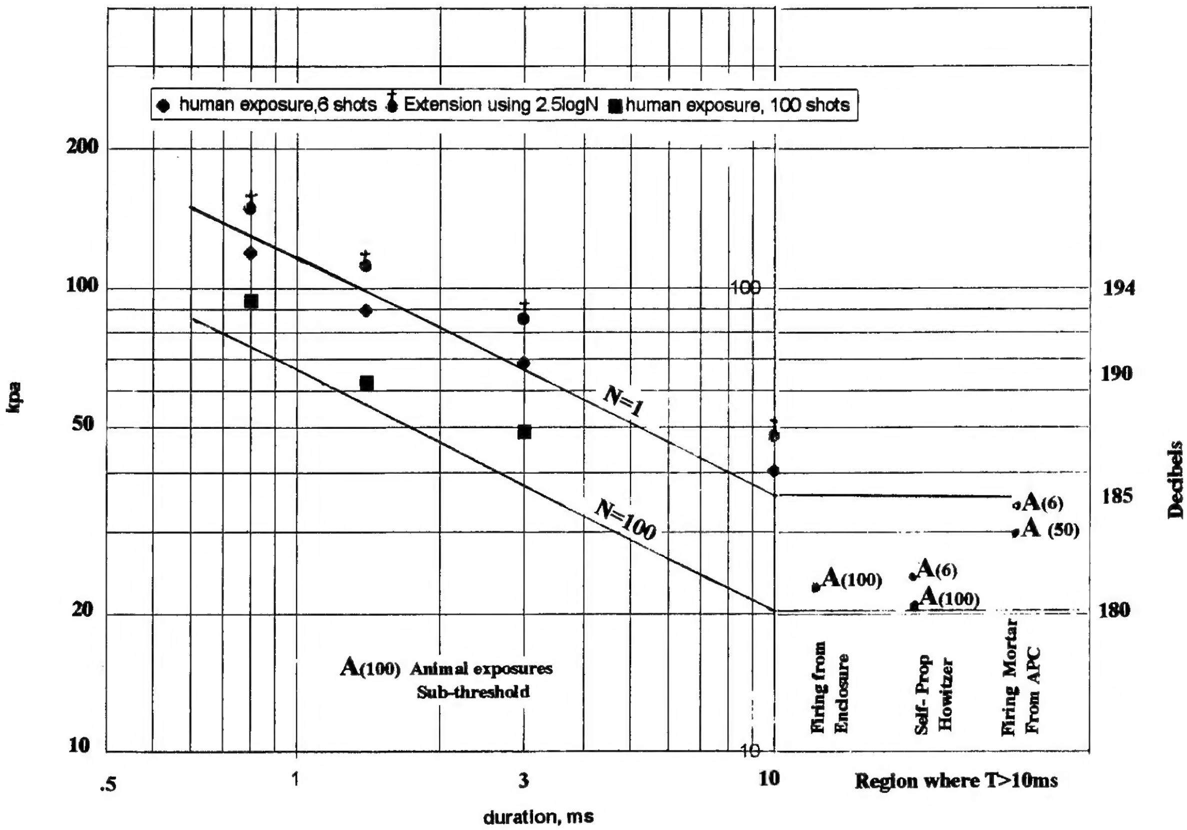
human exposure,6 shots
Extension using 2.5logN
human exposure, 100 shots
kpa
200
100
50
20
10
Decibels
194
190
185
180
N=1
N=100
A(6)
A (50)
A(100)
A(6)
A(100)
A(100) Animal exposures
Sub-threshold
Firing from Enclosure
Self- Prop Howitzer
Firing Mortar From APC
.5
1
3
10
Region where T>10ms
duration, ms

Figure 3

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Protective equipment	Weapon systems	

14. Abstract

This publication comprises papers from an RTO Lecture Series on Damage Risk From Impulse Noise.

High-level impulse noise (weapons noise) can cause auditory as well as non-auditory damage, which may limit combat effectiveness and may result in communication impairments as a consequence of noise-induced hearing loss. Recent research has shown that the present damage risk criteria have to be adjusted. This has major implications for the protective measures that have to be taken when using weapon systems. Protection equipment can be very effective when properly used, but everyday practice shows that the results in the field fall short of what could be achieved. In addition, hearing protection may interfere with communication. New developments in the design of hearing protectors: level dependent, active noise reduction... show how the protection and communication requirements can be combined and satisfied. Educational programs, emphasizing the new developments, may help to improve the effectiveness of hearing conservation and reduce the number of non-auditory accidents.

Topics covered by individual papers are:
- techniques and procedures for the measurement of impulse noise
- a draft ANSI standard on auditory risk criteria
- performance of hearing protectors
- communication and localisation with hearing protectors
- individual susceptibility to noise-induced hearing loss
- new perspectives in the treatment of acute noise trauma
- cost effectiveness of hearing conservation programmes
- non-auditory damage risk assessment for impulse noise

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